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THE SPINE

Medical & Surgical Management

Volume 1&2

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Foreword
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Vol. 1 & 2

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Dedicated to

My daughter Mia who makes my wife and I beam with joy every day and wish we could spend all the time in the world with her.

Alexander R Vaccaro

My parents who taught me the definition of determination, my loving wife Thomasina, and my mentors Drs Alexander R Vaccaro and Robert Byers.

Brian W Su

My mentors, fellow colleagues, and most of all to my wife, Mari.

Kazuhiro Chiba

My wife, Sue.

Marcel F Dvorak

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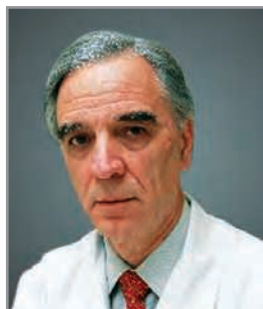


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Foreword

It is refreshing in this time of ever faster electronic flowing of information, to see some people still take the time to sit back, relax and reflect about what keeps us all professionally busy.

This new two-volume book on Spine Surgery is to be recommended for bringing a true 'evidence-based state of the art' on a vast array of spine topics. It feels like reading a succession of well thought about review articles.

Not only is it a multidisciplinary work bringing together respected professionals from all walks of life, but it was written by leading clinicians and scientists from around the globe, giving it a world-class standing. Evidence-based research is fine and necessary, yet, if not placed in the appropriate clinical context, can be ineffectual and sometimes harmful if misapplied.

These volumes should be found on the desk of all those who are involved regularly with matters related to the spine, be it clinically or in research.

Robert Gunzburg MD PhD
Editor-in-Chief
European Spine Journal



Preface

In no other field of medicine does the statement “*There is more than one way to skin a cat*,” apply more than to spinal surgery. Subtle differences in outcome are often seen when comparing direction of surgical approach, choice of surgical implant, and nonoperative versus operative care. Interestingly, variation in treatment has been often geographical. One example is the differences in surgical treatment of cervical myelopathy in Europe, Asia, and North America where surgeons argue for the merits between laminoplasty versus laminectomy and fusion. Our goal was to assemble a worldwide team of authors with the intent of emphasizing the most diverse but evidence supported methodologies for treating spinal pathology. When possible, an author from North America was paired with an author from another continent. The 135-chapter evidence-based text was then edited by the nine spine surgeons representing Brazil, Canada, China, Egypt, Germany, India, Japan, and the United States. Whether someone is a trainee or an expert spine surgeon, our hope is that this international textbook of spinal surgery is a glimpse into how the rest of the world is effectively caring for their patients.

Alexander R Vaccaro
Brian W Su
Kazuhiro Chiba
Marcel F Dvorak
H Michael Mayer
S Rajasekaran
Luiz R Vialle
Yan Wang
Magdy Gamal Youssef



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SECTION

1

General

Magdy Gamal Youssef

The Aging Lumbar Spine

Isaac L Moss, Howard S An, Stephen P Banco

Snapshot

» Etiology of Disc Degeneration

INTRODUCTION

The lumbar spine is composed of the five caudal-most fully segmented vertebrae of the spine. Each vertebra is a complex bone composed of several parts (Fig. 1.1). The *vertebral body* serves as the primary weight-bearing structure of the spine. The *lamina* and *pedicles* form the *spinal canal* that contains and protects the neural elements. A central *spinous process* and two lateral *transverse processes* protrude from the vertebrae and serve as attachment points for the paravertebral muscles and ligaments. The *superior* and *inferior articular processes* form synovial joints with the adjacent vertebrae known as the *facet joints*. Multiaxial motion between the vertebrae is achieved through a three-joint complex composed of an anterior intervertebral disc (IVD) separating two vertebral bodies and two posterior facet joints.

The facet joints are lined with articular cartilage and are surrounded by a capsule, typical of synovial joints elsewhere in the body. The IVD, however, has a unique structure consisting of an inner proteoglycan-rich gelatinous nucleus pulposus (NP), surrounded by the annulus fibrosus (AF), an organized fibrous ring with abundant type I collagen content. The entire structure is confined cranially and caudally by cartilaginous end plates.

With age, both the IVD and facet joints can degenerate displaying morphologic changes similar to other articulations in the skeleton, including joint space narrowing,

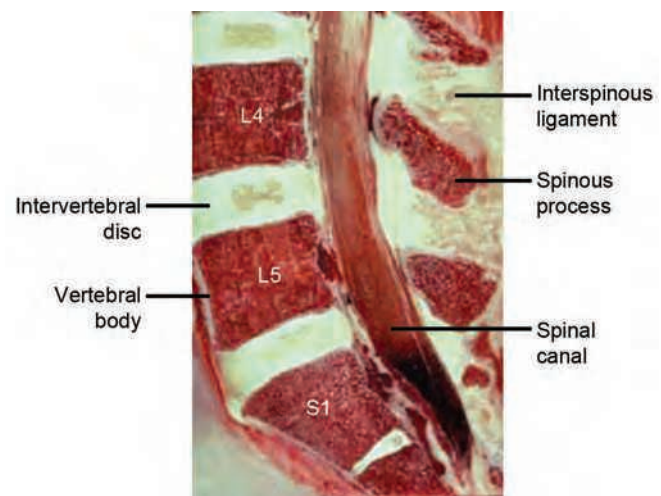


Fig. 1.1: Mid-sagittal cryotome section of the caudal lumbar spine demonstrating the relationship between the vertebrae, intervertebral discs, and the spinal canal.

subchondral sclerosis, and osteophyte formation (Figs. 1.2A and B).¹ In a segment of the population, this process can lead to a variety of clinical presentations including debilitating back pain, a common condition with enormous psychosocial and economic ramifications. It has been estimated that approximately 85% of individuals in the United States suffer from back pain at some point in their lifetime, with an annual prevalence of 15–45%.² The resulting direct and indirect economic costs have been estimated to be between 14 and 90 billion dollars per year.³ Despite the



Figs. 1.2A and B: Lateral X-ray of a normal lumbar spine (A) and a lumbar spine with advanced degenerative changes (B) including disc space narrowing (arrowheads), osteophyte formation (arrow), and spondylolisthesis (*).

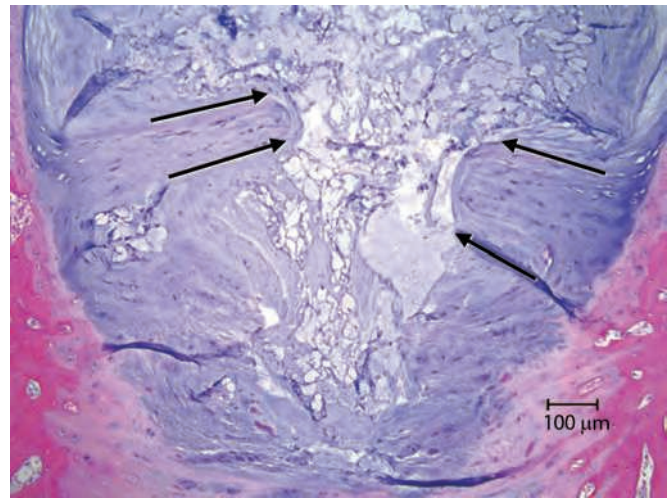


Fig. 1.3: Histologic section of rabbit intervertebral disc demonstrating migration of chondrocytes from the end plate into the nucleus pulposus (arrows). The pyknotic nuclei of notochordal cells undergoing apoptosis are visible in the center of the nucleus.

enormous clinical problem it represents, there is a lack of consensus as to how lumbar degeneration should be defined and which changes, particularly within the IVD, should be considered pathologic or just a normal part of aging.

This chapter will describe the development of the lumbar spine, the morphologic and biochemical features of the normal IVD and vertebrae, as well as the changes that occur with aging and pathologic degeneration. A better understanding of these processes is the first essential step in the development of novel therapies to treat and even potentially reverse the degenerative process and its consequence.

Development of the Spine

The axial skeleton is formed by condensation of mesenchymal cells in somites and their aggregation around the notochord. The segmentation of this perichordal tube results in condensed regions that form the vertebral bodies and noncondensed regions that form the IVDs.^{4,5} The notochordal cells proliferate within the IVD and synthesize an extracellular matrix rich in glycosaminoglycans, forming the original embryonic structure of the NP. The AF, on the other hand, is derived from the surrounding mesenchymal tissue. This gives rise to a distinct border between these two IVD components as well as very different tissue composition and properties.^{6,7} In the NP, the negatively charged aggregating proteoglycans produced by the notochordal cells generate an osmotic gradient that both

attracts and holds waters within the IVD. At birth, the population of notochordal cells within the IVD is estimated to be 2,000 cells/mm³.⁸ Shortly afterward, Fas-mediated mitochondrial caspase-9 activation⁹ results in notochordal cell apoptosis with a resulting cell density of 100 cells/mm³ at 1 year of age and almost none identifiable by late childhood. As the notochordal cell population dwindles, chondrocytic cells migrate from the cartilaginous end plate to repopulate the NP (Fig. 1.3). These cells synthesize both proteoglycan and type II collagen in an effort to maintain extracellular matrix homeostasis.¹⁰ Since these migrated chondrocytes are believed to be the major NP cell type in the adult IVD, NP and articular cartilage biology share many similar features.

The AF, derived from the mesoderm, is composed primarily of type I collagen organized into concentric lamellae synthesized by a fibrocyte-like cell population (Fig. 1.4). The collagen fibrils within the annulus are oriented approximately 30° from the long axis of the spine. Fibrils within each layer are parallel and run in opposing directions to adjacent layers. This organization confers significant tensile strength to AF tissue, which is responsible for resistance to tensile and shearing loads placed on the IVD. Only a small percentage of the dry weight of the AF is made up of proteoglycans. With aging, the distinct border characteristic of the developing NP and AF is lost, resulting in fibrous and highly organized outer AF, and an inner AF with mixed fibrocartilaginous characteristics.

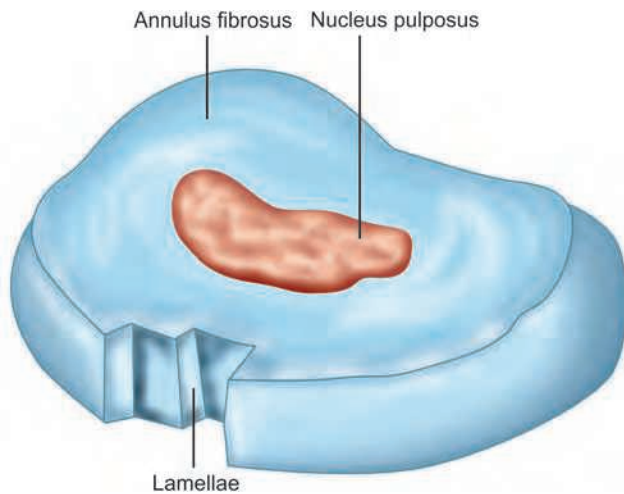


Fig. 1.4: The intervertebral disc composed of a gelatinous nucleus pulposus, surrounded by a fibrous annulus fibrosus. The annulus is composed of concentric lamellae with collagen fibers running in alternating directions, angles approximately 30° from the vertical axis of the spine.

The bony vertebral bodies and cartilaginous end plates are formed by mesenchymal cells above and below the IVD. In early life, blood vessels permeate through these structures providing the disc with nutrients.¹¹

By the third decade of life, the blood vessels that supply the center of the disc have receded. As a result, nutritional support to the IVD comes from diffusion through the end plate and outer AF.¹² The cell density within the IVD decreases to a level lower than almost any other tissue in the body as the disc grows with age and more extracellular matrix (ECM) is laid down.¹³ Much of this sparse cell population is found in the regions closest to the source of nutrition near the periphery of the IVD.

When development is complete, the IVD is a relatively acellular, avascular tissue with little potential for self-repair. As a consequence of this process and the constant biomechanical demands placed on the spine, the balance in production and degradation of extracellular matrix components within the NP and AF becomes disturbed with aging. This can give rise to the morphologic appearance of IVD degeneration, and sometimes, symptomatic discogenic low back pain (LBP).

Biochemistry of the Intervertebral Disc

The biochemical composition of the individual components of the spine dictates the biomechanical behavior

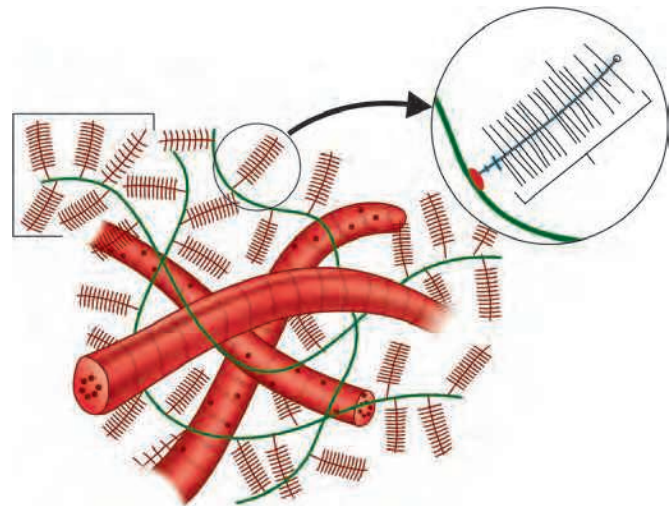


Fig. 1.5: Schematic drawing of the major extracellular matrix component of the nucleus pulposus. Large, predominantly type 2 collagen fibers (pink) are randomly arranged throughout the matrix. Aggrecan molecules (circular inset), composed of highly charged chondroitin sulfate and keratan sulfate monomers connected to a core protein, surround the collagen fibers. Multiple aggrecan molecules are connected to long hyaluronan backbones (green) via link protein to form large proteoglycan aggregates.

of the various structures of the spinal motion segment. Biochemical changes within the IVD are considered the primary drivers of the degenerative process and therefore will be the focus in this section.

The IVD and hyaline cartilage share a similar extracellular matrix molecule profile, likely due to the similar cell type populating both tissues (Fig. 1.5). It is estimated that 60% of the dry weight of the AF and 20% of the dry weight of the NP is made up of various collagen types, making it the most abundant protein in the disc. Both fibrillar (collagen I, II, III, V, XI) and short helical forming (collagen VI, IX, XII) collagen types are present in the disc.¹⁴ Type II collagen is the predominant type within the NP, creating a disordered fibrillar framework for other matrix molecules and cell attachment. There is a shift to a predominance of organized type I collagen with progression from the center of the NP toward the AF. Approximately 80% of the collagen molecules in the outer AF are type I.

The structure and distribution of collagen molecules within the IVD change in at least three significant ways as degeneration progresses.¹ The AF and the NP become more fibrous tissues as a result of an increase in the ratio of type I to type II collagen in both structures. Advanced

glycation end products are formed and accumulate due to the nonenzymatic cross-linking of collagen molecules. Production of collagenases by disc cells is also augmented, leading to enzyme-mediated proteolytic cleavage of collagen fibers. The consequence of these events is a buildup of incompetent fibrous collagen that decreases the compliance of the NP, limits its overall swelling ability, and impairs resistance to compressive loading.¹⁵

Up to 50% of the dry weight of the NP and 20% of the dry weight of the AF is made up of proteoglycans. After collagen, these are the second most abundant group of extracellular matrix molecules within the IVD. Versican, lumican, decorin, biglycan, and fibromodulin are all found in measurable quantities within the IVD; however, aggrecan is by far the most abundant proteoglycan.¹ The NP's ability to attract and bind water is largely due to the highly charged nature of this molecule consisting of chondroitin-6 sulfate and keratan sulfate side chains bound to a core protein. The aggrecan of the IVD also forms large proteoglycan aggregates by binding to hyaluronan through interaction with link protein, further augmenting its ability of attracting water and maintaining disc hydration.

As the disc ages, there is a change in both the amount and character of aggrecan within the IVD. A reduction in both cell numbers and the rate of proteoglycan synthesis per cell leads to a decrease in overall aggrecan production. At birth, chondroitin sulfate is the most abundant glycosaminoglycan side chain present within aggrecan molecules. With age, however, there is a shift to a predominance of keratan sulfate side chains.¹⁶ Water-binding capacity and efficiency is diminished as both aggrecan and aggrecan-hyaluronan aggregates are subject to proteolytic degradation. Additionally, due to the large size of these molecules, the partially digested proteoglycans are not easily scavenged from the disc. Similar to the collagens, these molecules amass within the IVD and are subject to nonenzymatic cross-linking further contributing to the accumulation of advanced glycation end products.¹⁵

The principal proteolytic enzymes produced by native disc cells are a disintegrin and metalloprotease with thrombospondin motifs and matrix metalloproteinases (MMPs).¹⁷ The cells also produce natural antagonists to MMPs, namely, tissue inhibitors of metalloproteinases. These enzymes and enzymatic inhibitors, which are modulated by a number of biochemical stimuli including expression of growth factors and cytokines, are responsible for remodeling and maintenance of IVD matrix homeostasis. Clearly, a certain amount of tissue turnover is required to clear dam-

aged molecules. However, the balance between anabolic and catabolic metabolism within the IVD can be altered due to age-related metabolic changes, genetic predisposition, and biomechanical dysfunction. This balance is generally shifted toward intensified catabolism, thus producing the biochemical changes typical of degeneration.

The consequence of these biochemical changes in collagen and proteoglycan content and enzymatic activity within the disc is a limited ability to adequately dissipate both compressive loads and progressive mechanical incompetence. Additionally, the impaired swelling pressure within the degenerated disc leads to a reduction in exchange of waste and nutrients, further starving the few remaining disc cells, which are diffusion dependent. The progressively fibrous matrix also places increased stress on the mechanically sensitive disc cells. The intracellular response to this microenvironment can lead to increased cell death and/or further upregulation of type I collagen and proteolytic enzyme synthesis, possibly contributing to downward degenerative spiral.¹⁸

Biomechanics

Two adjacent vertebrae, the facets joints, an intervening IVD, and the various connecting ligaments form the functional spinal unit. The AF and end plates enclose the relatively incompressible hydrated NP. Both axial compression and eccentric loading result in even stress distribution across the cartilaginous end plate in nondegenerated IVD.¹⁹ In the unloaded condition, proteoglycans attract and hold water within the NP generating positive intradiscal hydrostatic pressure. When the spine is loaded, stress is transmitted through the compact subchondral bone of the end plate to the NP. This leads to an increase in pressure within the NP that, in turn, is transmitted to the organized lamellar structure of the AF and converted into tensile hoop stress resulting in altered spatial arrangement of the collagen network and a small amount of immediate decrease in disc height. If the load applied to the spine remains constant, slow outflow of fluid through the AF and end plates results in a viscoelastic creep phenomenon with the IVD continuing to lose height over time. When the load is eventually removed, the osmotic pressure generated by the proteoglycans within the healthy NP will cause an influx of fluid from the surrounding tissue to slowly recover the lost height.²⁰ There is, therefore, a regular diurnal variation in IVD height with progressive loss of height during the day when upright, and recovery when supine at night.

Many rehabilitation regimes designed for patients with discogenic back pain are based on the *in vivo* intradiscal pressure measurements in various functional positions reported by Nachemson and Morris.²¹ In their study of undegenerated human discs, the unsupported sitting position resulted in the highest recorded intradiscal pressure (0.8–1.5 MPa). Conversely, the lowest pressures were measured in the discs of relaxed, supine subjects (0.1–0.2 MPa). Lifting, especially with an anterior positioned load, and other strenuous activities resulted in a significant increase in intradiscal pressure. These general trends observed by Nachemson were confirmed in two more recent studies.^{22,23} These studies also found a significant decrease in intradiscal pressure in degenerated IVDs (see Fig. 1.3).

The mechanical properties of the IVD change from those of a viscous semi-fluid to properties closer to those of a solid as the nucleus degenerates and becomes fibrous with decreased proteoglycan and increased collagen content.¹ Stress distribution across the spinal motion segment becomes uneven as the more fibrous NP has a diminished overall swelling capacity and is unable to adequately conform to and transmit applied loads.²⁴ The AF becomes overloaded and structurally damaged, especially when eccentric loads are applied to the IVD. Nucleus pulposus containment eventually fails, often through the development of fissures within the AF, as the degenerative process proceeds. Degenerated IVDs demonstrate altered creep characteristics with larger and more rapid deformation with any given load, and slower recovery when the load is removed.²⁵ As the main load-bearing structure of the functional spinal unit fails, a higher portion of load bearing is transferred to the posterior elements. Osteoarthritic changes similar to other cartilaginous synovial articulations begin to manifest within the overloaded facet joints. While facet joint degeneration does not always progress in parallel to IVD degeneration, facet degeneration is not found in the absence of a degenerated IVD.²⁶

The degenerative cascade proposed by Kirkaldy-Willis and Farfan explains the pathogenesis of spinal motion segment degeneration through three progressive phases.²⁷ In the first “dysfunctional” stage, acute or repetitive injury can lead to the accumulation of microscopic damage within the disc and synovitis within facet joint. In the second “unstable” phase, diminished IVD height, in addition to facet capsule laxity and subluxation, leads to pathologic and potentially painful hypermobility of the degenerated spinal motion segment. Eventually, severe degenerative changes inducing disc osteophyte formation and facet

enlargement lead to the third “stabilization” phase with resolution of the hypermobility present in stage two. The majority of back pain episodes are thought to occur during the first two stages of degeneration. In the third stage, discogenic back pain is relatively uncommon; however, patients may remain or become symptomatic from spinal stenosis due to hypertrophy of the facet joint and disc bulging. Recent cadaveric studies in both the lumbar²⁸ and cervical spine²⁹ have supported this observation, reaffirming the relationship between spinal motion and disc degeneration.

Macroscopic and Radiographic Changes

The biochemical and biomechanical alterations within the IVD result in well-described macroscopic changes. This progressive deterioration is the basis of the grading system proposed by Thompson et al. based on gross pathologic changes visible as the disc degenerates.³⁰

As pathologic examination is not usually practical, clinicians rely on radiographic imaging to diagnose degenerative disc disease. On plain X-ray, disc space narrowing, end plate sclerosis, and osteophyte formation at the margins of the affected level characterize degeneration. In more severe cases, gas collections can be visible within the disc. Degenerative changes on magnetic resonance imaging (MRI) provide a more detailed assessment of the state of the IVD. However, clinical correlation with the radiologic finding is always important, as MRI abnormalities are found in a large percentage of asymptomatic individuals.^{31,32} On T2-weighted sequences, loss of NP hydration results in progressive loss of signal intensity. Pfirrmann et al.³³ described an MRI grading scale of degenerative changes, similar to the pathologic Thompson scale (Table 1.1 and Fig. 1.6). Tears within the AF are often visible,³⁴ as well as end plate signal changes, both of which can be indicative of degenerative disc disease (DDD). Modic et al.³⁵ classified end plate signal changes into two types: Modic type I changes, indicative of augmented marrow fibrovascularity, demonstrate decreased signal intensity on T1-weighted sequences and increased signal intensity on T2-weighted sequences; whereas, Modic type II changes are characterized by increased signal intensity on T1-weighted sequences and isointense or slightly increased signal on T2-weighted sequence. The correlation of these changes with back pain is still the subject of debate.^{36–39}

As degeneration within the disc progresses, arthritic changes in other parts of the spinal motion segment become evident on imaging. Degenerative changes within the facet joint can become clinically important, and severity can be graded with either computed tomography scans

Table 1.1: MRI classification of disc degeneration.

Grade	Structure	Distinction between AF and NP	Signal intensity	IVD height
I	Homogenous, bright white	Clear	Hyperintense, isointense to CSF	Normal
II	Inhomogenous with or without horizontal bands	Clear	Hyperintense, isointense to CSF	Normal
II	Inhomogenous, gray	Unclear	Intermediate	Normal to slightly decreased
IV	Inhomogenous, gray to black	Lost	Intermediate to hypointense	Normal to moderately decreased
V	Inhomogenous, black	Lost	Hypointense	Collapsed disc space

(MRI: Magnetic resonance imaging; AF: Annulus fibrosus; NP: Nucleus pulposus; IVD: Intervertebral disc; CSF: Cerebrospinal fluid).

Source: Adapted from Pfirrmann CW, Metzdorf A, Zanetti M, et al. Magnetic resonance classification of lumbar intervertebral disc degeneration. *Spine (Phila Pa 1976)*. 2001;26(17):1873-8.

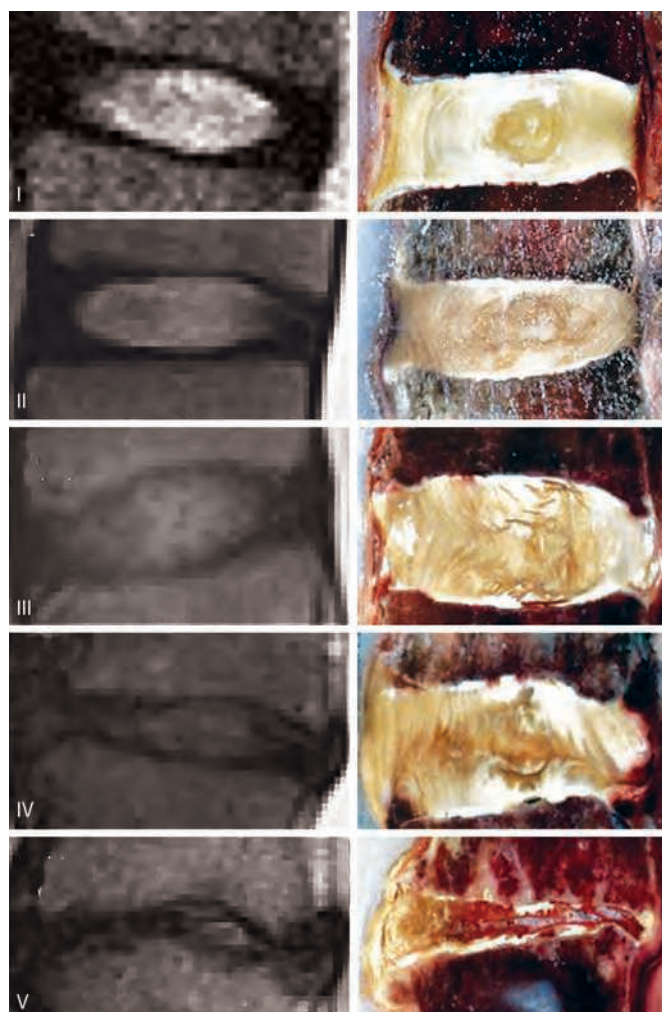


Fig. 1.6: Grading disc degeneration: T2-weighted magnetic resonance images (left panel) and gross pathology mid-sagittal sections (right panel) of intervertebral discs demonstrating progression of degenerative changes from Pfirrmann/Thompson Grade I, with no degeneration to Pfirrmann/Thompson Grade V, with severe degeneration and disc space collapse.

or MRI.^{26,40} The combination of both IVD and facet degeneration can lead to spinal stenosis and segmental instability, known as spondylolisthesis (Fig. 1.7). If degeneration progresses over multiple levels, alteration in both coronal and sagittal alignment can occur resulting in degenerative lumbar scoliosis or kyphosis. When asymmetric degeneration of the IVD and/or the facet joints occurs, the spinal motion segment is loaded unevenly. Over several years, an asymmetric deformity (i.e. scoliosis and/or kyphosis) can develop. The developing deformity further alters the load distribution, setting up a cycle, with the deformity again triggering additional asymmetric degeneration and inducing more asymmetric loading.⁴¹ These changes often occur in postmenopausal females or older men who have altered bone metabolism and some osteopenia.⁴² These patients may experience collapse of weak osteoporotic vertebrae and develop asymmetric bony deformity, which can contribute to further progression of either scoliosis or kyphosis. At each level, translational dislocations in either the coronal plane alone or three-dimensionally can occur in addition to spondylolisthesis, leading to rotational subluxation.⁴³

The degenerative changes not only lead to spinal deformity, but are also likely to result in the development of spinal canal narrowing, known as spinal stenosis. This stenosis, a result of disc narrowing, disc bulging, facet hypertrophy, and vertebral translation, can impinge on the neural elements in the spinal canal or neural foramen. Clinically, patients with stenosis can experience back pain and/or leg pain in the form of radiculopathy or neurogenic claudication.

ETIOLOGY OF DISC DEGENERATION

Lumbar spine degeneration is considered an unavoidable consequence of aging. In one anatomic study, macroscopic



Fig. 1.7: Mid-sagittal (left panel) and axial (right panel) T2-weighted magnetic resonance imaging of the lumbar spine of a 64-year-old woman who presented with both low back and bilateral leg pain. The hallmarks of disc degeneration are apparent at the L4-5 level (arrow head) on the sagittal including loss of nucleus pulposus hydration and disc space narrowing. Facet joint hypertrophic osteophyte formation is evident on the axial images (arrows). These degenerative changes have resulted in spondylolisthesis, with L4 slipped forward on L5 (left panel), and severe spinal stenosis (*, right panel).

disc degeneration was found in 98% of specimens above the age of 70 years, and in only 16% of specimens below the age 20 years.⁴⁴ Fortunately, while extremely common on pathologic examination and imaging, spinal degeneration is frequently asymptomatic.^{31,32} In patients with back pain, it can be a clinical challenge to determine which degenerated structures are the pain generators and which are incidental findings.

There are many etiologic factors that have been linked to the development of spinal degeneration. As discussed previously, the disc cells are responsible for maintenance of homeostasis within the IVD. Therefore, anything that impacts the microenvironment within the NP or alters disc cell metabolism and synthetic rate can accelerate the degenerative process. These factors can be environmental, mechanical, and/or genetic.

Intervertebral disc nutrition has been implicated as a major contributor to degeneration.⁴⁵ As detailed above, the blood vessels supplying the NP recede in the first two decades of life leaving the disc cells largely dependent on diffusion through the end plates and outer AF for nutrition.¹² As the end plates calcify with age, diffusion into

the IVD is impeded further. The cells at the center of the mature NP can be several millimeters from the nearest blood supply, severely limiting nutrient diffusion.¹² Viability of these cells is significantly impacted by the loss of nutritional support, leading to a decreased number of cells over time.⁴⁶ Lack of nutrients and low oxygen tension shift the metabolism of the remaining cells to the anaerobic pathway, leading to lactate production and lowered tissue pH. In these conditions, the rate of matrix synthesis by disc cells drops off further.^{47,48} The combination of a low number of viable cells and less matrix synthesis per cell shifts the balance of homeostasis within the disc to one of net catabolism. Systemic diseases that can alter vertebral blood supply, such as atherosclerosis,⁴⁹ have been associated with higher rates of disc degeneration. Smoking has also been linked to the development disc degeneration and back pain in several epidemiologic studies.^{50,51} The negative effects of smoking on the disc are thought to be mediated both through nutritional restriction^{52,53} and direct nicotine toxicity to disc cells.^{54,55}

Alteration in mechanical loading has also been implicated as a cause of disc degeneration, with changes

in the biomechanical environment leading to biochemical changes within the tissue.^{56,57} Excess, or asymmetric mechanical loading of the disc can lead to localized tissue trauma. Tissue repair will be minimal due to slow turnover of the disc matrix.⁵⁸ Prolonged mechanical loading can lead to a higher rate of apoptosis of IVD cells.⁵⁹ Additionally, excessive hydration or dehydration of the disc has been shown to significantly decrease the rate of matrix synthesis.^{60,61} The combination of repetitive microtraumas and the decreased turnover and synthetic rate of disc cells and matrix, ultimately leads to progressive structural failure of the disc, making it more susceptible to further injury.

Genetic susceptibility has also been implicated as major contributing factor to disc degeneration. The so-called “Twin Spine Study”⁶² compared the rates of IVD degenerative changes in monozygotic twins in three countries with discordant exposure to occupational or sport-related spinal loading. The data demonstrated that genetic factors are the primary predictor of disc degeneration, with heredity accounting for up to 74% of the variance present in the adult population. This dispelled the previously held belief that mechanical injury was the strongest driver of degeneration. Further work by Videman et al.⁶³ demonstrated that polymorphism within vitamin D receptor gene was associated with disc degeneration. Other gene polymorphisms including aggrecan,⁶³ interleukin-1 and COL9A3,^{64,65} COL9A2,⁶⁶ collagen IX and XI,⁶⁷ and MMPs-3⁶⁸ have been linked to the development of disc degeneration.

Chronic low-grade infection has recently received some attention as a potential contributor to disc degeneration and LBP. Albert et al.⁶⁴ cultured herniated disc material from patients undergoing discectomy. The study found microorganisms to be present in 46% of herniations, with the anaerobic bacteria *Propionibacterium acnes* being the most common isolate detected. The study further demonstrated a statistically significant higher rate of type 1 Modic changes in patients with disc material infected with anaerobic bacteria. A follow-up randomized controlled trial demonstrated improved clinical outcomes in patients with chronic back and previous herniated discs after 100 days of antibiotic therapy.⁶⁵ The generalizability of these exciting findings to the general population of LBP patients has yet to be determined.

Pain Generators

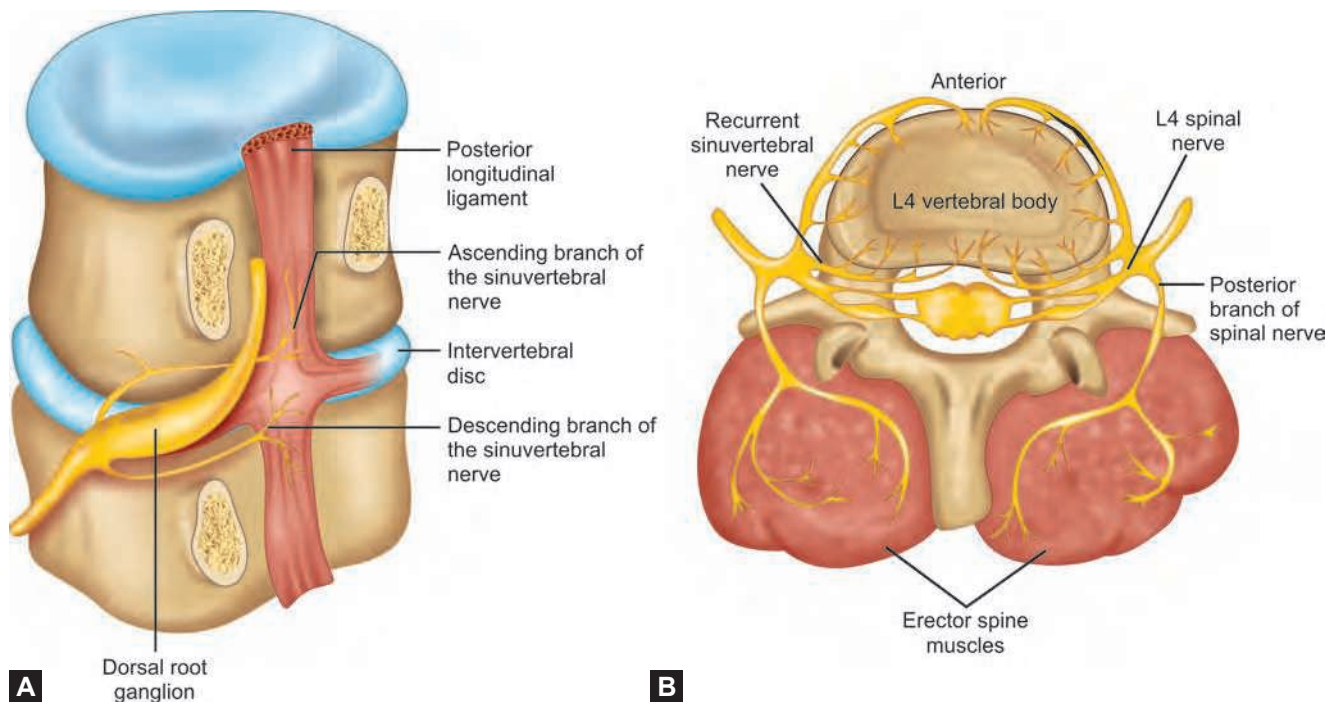
An understanding of the biomechanical and biochemical processes as well as the etiologic factors leading to spinal

degeneration is important. However, from a clinical perspective, an essential question remains to be answered—what is the source of pain in the degenerating spinal motion segment? This is especially relevant as there is a poor correlation between the morphologic signs of degeneration and back pain.⁶⁶ No single answer to these questions has emerged; however, it has become clear that several sources of pain exist.

Pain originating from the IVD, termed *discogenic pain*, has long been implicated as a major player in the process; however, its etiology is not well understood. The central end plate and the periannular tissues have the most abundant nerve supply of the IVD.⁶⁷ The outer rim of the AF is thought to contain the bulk of IVD nociceptive fibers arising from the sinuvertebral nerve, a meningeal branch of the spinal nerve originating from the dorsal root ganglia (Figs. 1.8A and B). It has been demonstrated in animal models that the caudal IVDs may be innervated by the L1 or L2 dorsal root ganglia through the sympathetic trunk.⁶⁸⁻⁷¹ Thus, discogenic back pain may be referred to the groin (i.e. the L2 dermatome). There is currently debate in the literature as to whether or not this finding may be of diagnostic or therapeutic value.^{72,73}

Discography, injection of fluid into the IVD, has been used as a provocative test for discogenic pain; however, its accuracy in predicting the source of pain in response to treatment is still quite controversial.⁷⁴ Stretch of an abnormal AF, extravasation of foreign tissue into the peridural space, and pressure on adjacent nervous structures are thought to be mechanism for pain generation. In vitro experiments have demonstrated that human IVD cells increase production of nerve growth factor when exposed to interleukin-1 β and tumor necrosis factor- α , both important proinflammatory cytokines.⁷⁵ This may promote infiltration of nociceptive nerve fibers into the disc and lead to back pain. Other authors have attempted to find differences in morphologically degenerate discs with varying degrees of clinical symptoms. Keshari et al. found that proteoglycan, lactic acid, and collagen ratio as measured by nuclear magnetic resonance spectroscopy differed in symptomatic and nonsymptomatic abnormal IVDs.⁶⁶ These findings may serve as the basis for a diagnostic test at some point in the future.

The facet joints have been noted to be a major source of pain since early in the 20th century.^{76,77} The load to the facets is maximal with lumbar hyperextension, and is further increased when disc height is lost as a result of degeneration.⁷⁸ Experiments using both provocative and



Figs. 1.8A and B: Innervation of the intervertebral disc. (A) Ascending and descending branch of the sinuvertebral nerve shown arising from the dorsal root ganglion (DRG). (B) Course of the recurrent sinuvertebral nerve from the DRG through the vertebral foramen innervating the outer annulus fibrosus.

Source: Raj PP. Intervertebral disc: anatomy-physiology-pathophysiology-treatment. *Pain Pract.* 2008;8(1):18-44.

therapeutic intra-articular injections confirmed the facet joints to be a significant pain generator in patients with LBP.^{79,80} Additionally, both sensory and autonomic nerve fibers as well as neurotransmitters have been shown to be present in the facet capsule.⁸¹ The lumbar facet joints are segmentally innervated by the medial branch of the dorsal rami.⁸² Thus, intra-articular facet joint injections, and medial branch block or ablation is a commonly employed treatment for chronic LBP. Evidence for the efficacy of these treatments remains unclear, especially in the long term.⁸³⁻⁸⁵

Nerve root compression or irritation can also be a mechanism for pain production in lumbar degeneration. While this most often presents as radiculopathy, with pain radiation to the dermatomes of the lower extremities, nerve compression can also cause isolated back pain. The pathophysiologic basis for neurogenic pain is a subject of debate; however, recent studies have demonstrated increased neuropathy, ectopic discharge, and mechano-sensitization of nerve roots when exposed to NP tissue, a situation commonly found in the degenerated lumbar spine.⁸⁶

As more information emerges in the literature, it is clear that the area of pain generation deserves further study

both mechanistically and diagnostically in order to enable researchers and clinicians to develop and plan appropriate therapies.

Biologic Therapy for Lumbar Degeneration

Although our understanding of the mechanisms of spinal degeneration has advanced significantly, the current standard of care for patients with lumbar degeneration is aimed at symptomatic control rather than reversal of the disease process. Nonsurgical therapeutic modalities including patient education, medications, exercise therapy, and occasionally various types of injections are commonly employed. In a small number of patients with unrelenting symptoms, surgical intervention to decompress, stabilize, or even replace the affected motion segments is recommended. While these interventions can be effective, they come at a high cost and put patients at risk of complications. As discussed previously, spinal degeneration is believed to begin with changes in the NP of the IVD. Thus, biologic repair to slow or reverse the early nucleus degenerative process is an attractive alternative to the current

end-stage mechanical treatment approaches. Successful biologic repair strategies require a consideration of one or all of the following components: delivery of cells, the application of therapeutic molecules, and the supplementation of matrix.¹¹

The density of cells present in the NP decreases significantly with aging and degeneration.¹³ In order for tissue repair to be possible, a new population of cells is necessary to produce appropriate extracellular matrix molecules and supplement the existing population. This can be achieved by implantation of new healthy cells into the disc, and/or by stimulation of native cell proliferation with bioactive molecules. A small clinical study examined the utility of autologous disc cell harvest, followed by *ex vivo* expansion and subsequent reimplantation.⁸⁷ While the possibility of supplementation with autologous cells is attractive, concerns with the practical application of this strategy and the infrastructure necessary to harvest and expand the cells *ex-vivo* have prompted the investigation of other source of cells. Pluripotent cells, such as mesenchymal stem cells, are interesting candidates for cell supplementation as they can be harvested from several sources and are highly metabolically active in the proper environment. They have thus become the focus of many studies. Experiments conducted both *in vitro* and *in vivo* have demonstrated that mesenchymal stem cells can be successfully differentiated into chondrocyte-like cell populations. Under appropriate conditions, these cells can express IVD matrix proteins and cell surface markers.⁸⁸⁻⁹⁹ Based on successful recent *in vivo* work with an ovine model of disc degeneration,¹⁰⁰ a phase 2 human clinical trial using cell-based therapy is currently underway. The study is designed to determine the safety and initial efficacy of injecting mesenchymal precursor cells in a hyaluronic acid carrier into the degenerating IVDs. Results of this study have yet to be released; however, this represents an important step in the translation of this technology from the laboratory to clinical application.

The delivery of bioactive molecules to alter the catabolic environment of the degenerating NP is another cornerstone of a successful regenerative strategy. There are four basic categories of potentially therapeutic bioactive molecules: anticatabolics, mitogens, chondrogenic morphogens, and intracellular regulators.¹¹ The chondrogenic morphogens, which include transforming growth factor- β and the bone morphogenetic protein (BMP) family, have been the focus of much investigation in this field. Proteoglycan and collagen synthesis is increased in response to transforming growth factor- β treatment of both healthy

and degenerated IVD cells *in vitro*.¹⁰¹⁻¹⁰³ The BMP family of growth factors is currently used clinically to promote fracture healing and spinal fusion as they have been shown to induce osteogenesis. Interestingly, disc cells treated with BMP-2 and BMP-7 (osteogenic protein-1) show increased production of collagen type II and proteoglycans, without osteogenic effects seen in other environments.¹⁰⁴⁻¹⁰⁷ In preclinical animal experiments, direct injection of a single dose of BMP-7 into degenerating discs resulted in improved disc height, restoration of viscoelastic biomechanical properties, and healthier functional metabolism.^{108,109} Another member of the BMP family, growth differentiation factor-5, was found to improve IVD cell viability and extracellular matrix production *in vitro*, and to curb progression of degeneration in a preclinical model.¹¹⁰ Several other potentially therapeutic molecules, including interleukin-1 receptor antagonist, platelet-derived growth factor, and insulin growth factor-1, are currently being investigated for their effects on IVD cells and disc degeneration.

Despite encouraging *in vitro* and *in vivo* studies, there is some concern that a single direct injection of a therapeutic molecule into the IVD may not be sufficient to stimulate and maintain the repair process. Gene therapy has been proposed as a method to achieve long-term sustained expression of stimulatory molecules from cells within the IVD. The potential for immune reaction and the spread of disease have raised safety concerns with the employment of viral vectors to deliver gene therapy elsewhere in the body. Due to its relative avascularity, cells of the immune system have limited access to the IVD and it is considered to be an immune-privileged environment. Thus, viral transfection of both native disc cells and exogenous chondrocytes with vectors to promote expression of several therapeutic factors has been attempted. The genes of interest include both intracellular regulatory proteins and growth factors. Both cell culture work and *in vivo* experiments examining the delivery of the transcription factor Sox-9, known to be an important regulator of the chondrocytic phenotype, to nucleus cells via a recombinant adenovirus have demonstrated upregulation of proteoglycan synthesis and reversal of early degeneration.^{111,112} Increased cell viability and augmented production of extracellular matrix molecules have also been demonstrated with adenoviral transfection of both animal and human NP cells with several growth factors including transforming growth factor- β 1, BMP-2, BMP-7, and insulin growth factor-1.¹¹²⁻¹¹⁴ Data from these experiments have served as a proof of principle that transfections of cells with stimulatory genes and subsequent implantation of

these altered cells into the degenerating disc may represent an effective strategy for cell therapy and the delivery of therapeutic molecules in a single treatment.

Scaffolds to serve as cell or drug carriers and supplement the degenerating extracellular matrix are the final component of a successful IVD tissue-engineering strategy. A wide variety of candidate materials have been investigated. A scaffold must provide a favorable microenvironment for cell growth, migration, and synthesis of extracellular matrix in order to be successful. Ideally, constructs must have mechanical properties capable of withstanding the loads within the IVD in the short term, and then incorporate and remodel as the disc regenerates.¹¹⁵ Many of the scaffolds studied are designed by combining fibrillar molecules and glycosaminoglycans in an attempt to re-create the normal matrix components of the IVD.¹¹⁶⁻¹²⁰ This aspect of regenerative therapies continues to be the subject of active investigation.

SUMMARY

The lumbar spine is a complex structure elegantly designed to support upright posture and protect the neural elements. Lumbar degeneration occurs as an inevitable part of aging and results in altered biochemical and biomechanical function as well as anatomic abnormalities. These changes result in a wide spectrum of symptoms, from completely asymptomatic to debilitating pain and functional decline. As our understanding of the makeup and function of the various components of the lumbar spine advances, opportunities for interventions to halt or reverse this process at early stages are evolving. In the future, these interventions may allow the next generation of physicians to change, for the better, the way we treat the aging lumbar spine.

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Anatomy of the Cervical, Thoracic, and Lumbar Spine

Ahmed S Mohamed, Alex Ching

Snapshot

- » Development
- » Musculoskeletal Anatomy
- » Anatomy of Neurologic Structure
- » Vascular Anatomy of the Spine
- » Functional Anatomy/Structural Spinal Stability

INTRODUCTION

The vertebral column is composed of alternating vertebrae and intervertebral (IV) discs supported by spinal ligaments and muscles. All of these elements, bony, cartilaginous, ligamentous, and muscular, are essential to the structural integrity of the spine. The spine serves three vital functions: protecting the spinal cord and nerves, transmitting the weight of the body, and providing a flexible axis for movements of the head and the torso. The vertebral column is capable of extension, flexion, lateral bending, and rotation. However, the degree to which the spine is capable of these movements varies according to region.

The spine is a segmental column of similar formed bones that constitutes the major part of the axial skeleton. Its individual elements are united by a series of IV articulations to form a flexible, although neuroprotective, support to the trunk and limbs.¹

The inclusion of all articular tissues, the overlying spinal muscles, and the segmental contents of the vertebral canal and IV foramen into a single functional and anatomic unit was first suggested by Junghanns.² Originally called the “motor” segment, this unit represents a useful concept that stresses the developmental and topographic interdependence between the fibrous structures that surround the IV foramen and the functioning of the structures that pass through it.

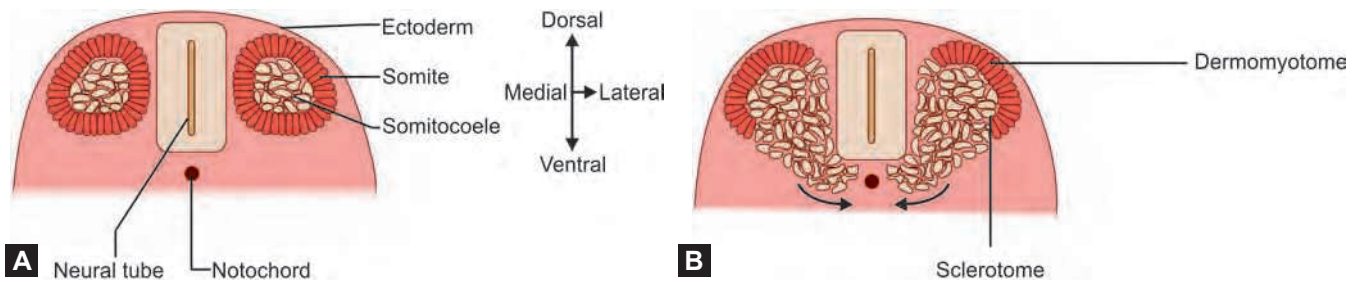
DEVELOPMENT

Overview

Much of the understanding of human embryology has been elucidated from extensive experimental manipulations of organisms such as *Drosophila melanogaster*, chicken, and mice.^{3,5,6} Human embryology, from conception through the embryonic and fetal periods and, finally, birth, has been characterized in detail. The development of musculoskeletal structures associated with the trunk of the human body is a multistep process involving differential gene expression as well as cell interactions and cell signaling between precursor tissues. This process occurs during the 4th through 8th weeks of development, with a mass of ectodermal cells dividing and forming a tube that migrates cranially in the midline between the ectoderm and endoderm. The notochord arises from cells in the primitive streak. It develops from cranial to caudal by adding cells. The notochord itself induces formation of the neural groove that closes by the end of the 4th week, forming the neural tube. Failure of this step is believed to be the cause of myelomeningocele.³⁷

Bony Development

The precursors to the vertebrae are the somites that form the paraxial mesoderm. The positional information of the



Figs. 2.1A and B: Schematic of somite differentiation. (A) Newly formed somites consist of an epithelium and a mesenchymal somitocoele. (B) Sclerotomal cells migrate medially around the notochord and will eventually become the vertebrae.

somite is imparted early in gestation and a displaced somite will continue to have the morphology of the intended location.⁶ All 30 pairs of somites are present at 4.5 weeks of gestation. The sclerotomal cells from the paired somites migrate medially around the notochord. They separate it from the dorsal neural tube and ventral primitive gut. The neural arches develop from the ventral to dorsal and enclose the neural tube. The spinal nerves and dorsal root ganglia arise at the level of the somite and enter the myotome at the beginning of the 6th week of gestation. Neural crest cells then accumulate just before the cranial closure of the neural tube and are situated between the neural tube and the somites. These cells are the precursors to the peripheral nervous system (Figs. 2.1A and B).

The formation of the vertebrae is dependent on the highly coordinated migration of sclerotomal cells both toward the midline and along the rostral/caudal axis.^{7,8} Soon after epithelial-mesenchymal transformation, cells from the ventral/medial sclerotome migrate toward the notochord, where they will contribute to the vertebral body and IV discs. This is followed by the migration of the lateral sclerotomal cells dorsally to form the vertebral pedicles and the laminae of the neural arches. Resegmentation of the sclerotome is intimately linked to the specification of the rostral and caudal domains early in somitogenesis. Disruption of rostral/caudal polarity after somite formation has also been shown to impact resegmentation, though to a lesser extent.⁴ In paraxis-deficient embryos, ventral cartilage fails to segment into vertebral body and IV discs, while the lateral neural arches are unaffected. For example, disruption of the caudal identity of somites through inactivation of the Notch pathway leads to fused vertebral bodies and an absence of neural arches.

At birth, only 30% of the spine is ossified. The spine has a well-established pattern of growth throughout the infantile, juvenile, and adolescent period, during which time

the spine will nearly triple in length. The rate of growth accelerates from birth to 2 years of age; it becomes steadier from age of 2 to 10 and then starts to accelerate again during the prepubescent period.

Intervertebral Disc Development

The genesis of the IV disc is intimately linked to somite polarity and sclerotome resegmentation and as such is dependent on the Notch/Mesp2 signaling. The annuli fibrosi of the IV discs forms from condensed mesenchyme derived from the somitocoele at the border of the rostral and caudal domains during resegmentation.

Development of the annuli fibrosi and its maintenance in adults is dependent on members of the transforming growth factor beta (TGF- β) superfamily.^{9,10} Inactivation of TGF- β type II receptor (Tgfr2) in type II collagen-expressing cells results in an expansion of Pax1/Pax9 expression and the loss of IV discs. GDF-5 and BMP-2 promote cell aggregation and expression of the chondrogenic genes instead of osteogenic genes in the IV discs.

Musculature Development

The dorsolateral subpopulation of somatic cells is called the dermomyotome. These cells maintain their segmental arrangement and give rise to a new layer of cells, the myotome, which provides the skeletal musculature for its own segment. The “rearrangement” or organization of sclerotomes into definitive vertebrae causes the myotomes to overbridge the IV discs, allowing for movement of the spine. The remaining subset of cells, after migration of the myoblasts from the myotomes, is referred to as the dermatome, and forms the dermis on the dorsal side of the embryo.

A segmental nerve associates with the dermatome and the myotome. This early contact of the nerve and differentiating muscle not only provides motor innervation, but

also provides sensory innervation, which develops to recognize pressure, touch, and temperature from the skin surfaces. This area of skin is supplied by branches of a specific single spinal nerve and, eventually, contributes to the dermis of the skin and is known as a dermatome. Although growth causes some changes in the original segmental size, these distinct dermatome patterns are maintained throughout life. The dermis on the ventrolateral side of the embryo is derived from the somatic mesoderm.^{3,5}

MUSCULOSKELETAL ANATOMY

Bony and Joint Anatomy

The vertebral column is flexible and formed of series of bones called vertebrae. The average spine consists of 33 vertebrae, seven cervical, 12 thoracic, and five lumbar plus five sacral and four coccygeal.

The vertebrae in the *cervical region* are much smaller than those found in other parts of the human spine.

Morphologically, the top two vertebrae of the spine are highly unique and form a set of articulations that provide a disproportionate amount of overall cervical mobility through these segments. The atlas serves as a ring or washer that the skull rests upon and articulates in a pivot joint with the dens or odontoid process of the axis (Fig. 2.2). Approximately 50% of flexion and extension of the neck happens between the occiput and C1; similarly, 50% of the rotation of the neck happens between C1 and C2.¹¹⁻¹³ There is no articular disc between these upper two levels of the spine.



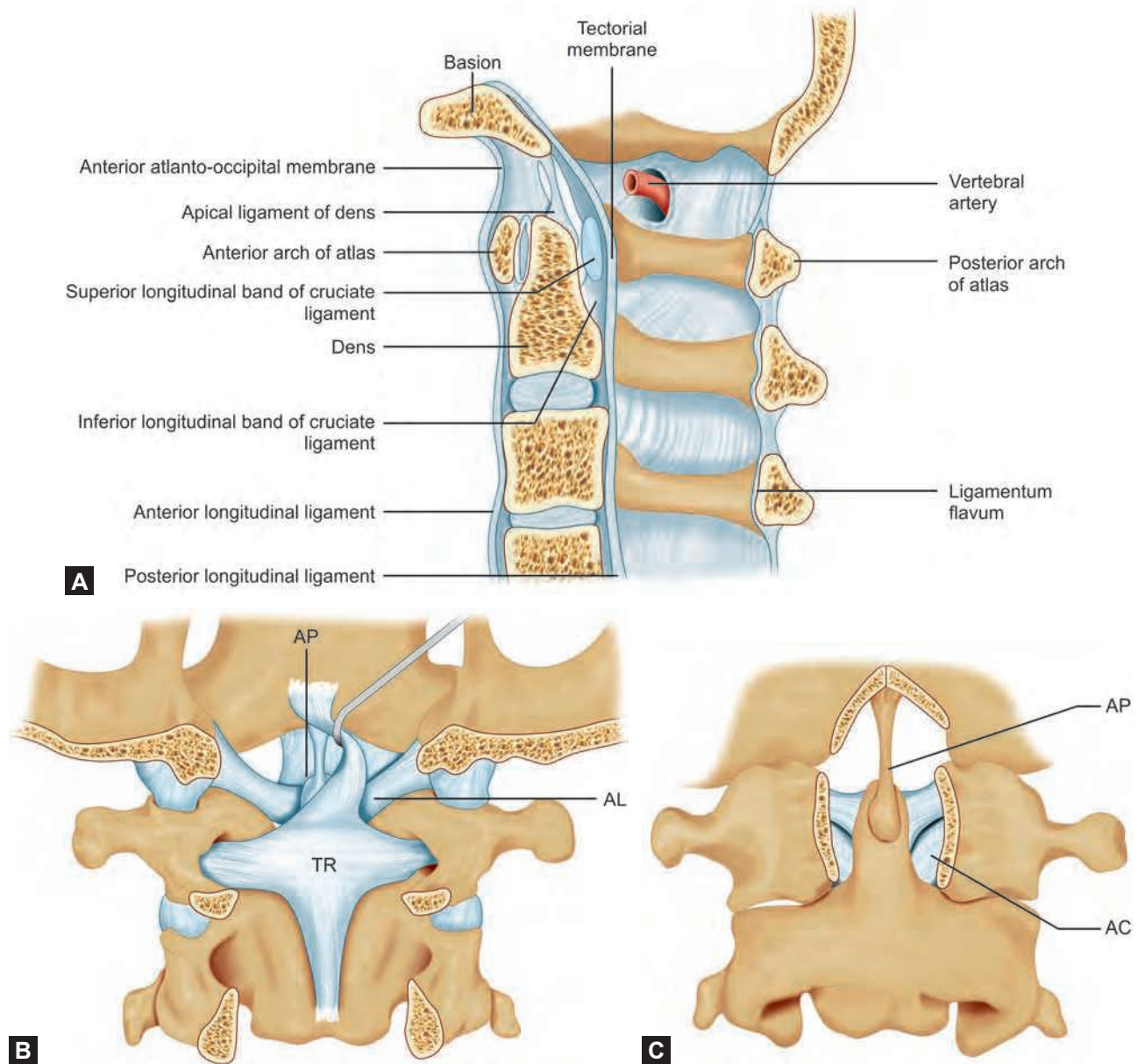
Fig. 2.2: Unique C1-C2 anatomical relationship.

The atlas (C1) is ring shaped and does not have a body, unlike the rest of the vertebrae. Fused remnants of the atlas body have become part of C2 (the axis), where they are called the odontoid process, or dens. The odontoid process is held in tight proximity to the posterior aspect of the anterior arch of the atlas by the transverse ligament, which stabilizes the atlantoaxial joint. On each C1, lateral mass is a superior and inferior facet joint. The superior articular facets are kidney shaped, concave, and face upward and inward. These superior facets articulate with the occipital condyles, which face downward and outward. The relatively flat inferior articular facets face downward and inward to articulate with the superior facets of the axis. The joints are inclined at an angle of 45° from the horizontal plane and 85° from the sagittal plane. This alignment helps prevent excessive anterior translation and is important in weight bearing.

The craniocervical junction and the atlantoaxial joints are secured by the external and internal ligaments. The external ligaments consist of the atlanto-occipital, anterior atlanto-occipital, and anterior longitudinal ligaments. The internal ligaments, by allowing spinal column rotation, provide further stabilization and prevent posterior displacement of the dens in relation to the atlas and consist of the following (Figs. 2.3A to C):

- The transverse ligament holds the odontoid process in place against the posterior atlas, which prevents anterior subluxation of C1 on C2.
- The accessory ligaments arise posterior to and in conjunction with the transverse ligament and insert into the lateral aspect of the atlantoaxial joint.
- The apical ligament lies anterior to the lip of the foramen magnum and inserts into the apex of the odontoid process.
- The paired alar ligaments secure the apex of the odontoid to the anterior foramen magnum.
- The tectorial membrane is a continuation of the posterior longitudinal ligament to the anterior margin of the foramen magnum.
- The 3 cm × 5 mm accessory atlantoaxial ligament not only connects the atlas to the axis, but also continues cephalad to the occipital bone; functionally, it becomes maximally taut with 5–8° of head rotation, lax with cervical extension, and maximally taut with 5–10° of cervical flexion; it seems to participate in craniocervical stability.^{14,15}

In the subaxial cervical spine, the minimal weight-bearing status of the cervical vertebrae allows the bones to have small bodies. The mobility of the cervical spine is



Figs. 2.3A to C: Ligamentous structure of the upper cervical spine. (A) Sagittal view; (B) Posteroanterior (PA) view, (C) Anteroposterior (AP) view.

permitted by the articular processes, which lie at approximately 45° from the horizontal plane. Most cervical vertebrae have bifid (split) spinous processes that serve as attachments to the muscles of the neck. The transverse processes of the cervical vertebrae have a transverse foramen laterally; from C6 and above, this serves as the passageway for the vertebral artery on its way into the cranium. Articulations include disc-vertebral body articulations, uncovertebral joints, and zygapophyseal (facet) joints.

The *thoracic spine* includes 12 vertebrae that appear to have slightly larger bodies than those of the cervical region. The size of the vertebral bodies increases in proportion to the amount of weight borne by the bone. The vertebral body becomes larger as one moves lower in the spinal column. The thoracic vertebrae have characteristically long spinous processes and these processes are generally angled downward throughout the 12 vertebrae. There are specialized facet joints where the ribs articulate with the vertebral

body and/or the transverse processes. The orientation of the articular facets in the thoracic level is at an approximate 60° angle from the horizontal plane. Each thoracic vertebra articulates with both the vertebra above and the vertebra below as well as with the IV disc between the adjacent vertebral bodies. The head of the rib articulates with a vertebral body in one location (vertebra 10–12) on each side of the bone or in two locations (vertebra 1–9). Most ribs (vertebra 1–9) also articulate with the transverse process.

The *lumbar spine* consists of five vertebrae, each larger than one above it. The spinous processes in the lumbar spine are characteristically short and thick. The articular processes generally lie in the sagittal plane, with variations being common.¹⁵⁻¹⁷ This is especially in the transitional vertebrae: the first lumbar having characteristics of the thoracic as well as the lumbar facets, and the last lumbar transitioning into the sacral facet alignment.

The body of a typical lumbar vertebra articulates with the level both above and below through the IV disc and facet joints. The fifth lumbar vertebra articulates with the sacrum at the interarticular, and in some cases the transverse process of one or both sides will be elongated and articulated with the sacrum (sacralization of the lumbar vertebra).

The *sacrum* consists of five fused vertebrae, giving the appearance of one solid bone. The vertebral canal continues through the sacrum, with the IV foramina aligning either anteriorly or posteriorly. The sacrum provides the connection between the lower extremities, pelvic ring, and the spine. The first sacral vertebra articulates with the inferior articular facets of L5. Laterally, the sacrum articulates with the ilium at the right and left sacroiliac joints.

Inferiorly, the sacrum articulates with the most superior coccyx bone. Three or four small bones comprise the *coccyx*. These small bones have no vertebral foramen and thus are not like other bones of the spine.

The *IV disc* serves multiple functions: as a primary stabilizer of the vertebral bodies, as a shock absorber, and a hydraulic jack. Around its circumference, a lamina of fibrous tissue and fibrocartilage forms the annulus fibrosus; and, at its center, a soft, pulpy, highly elastic substance, of a yellowish color, projects considerably above the surrounding level when the disc is divided horizontally. This pulpy substance (the nucleus pulposus), especially well developed in the lumbar region, is the remnant of the notochord. The laminae are arranged concentrically; the outermost

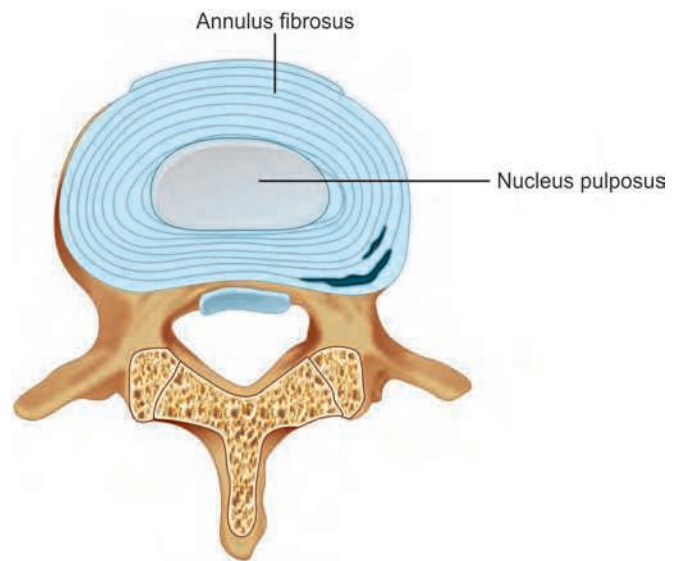


Fig. 2.4: Intervertebral disc.

consist of ordinary fibrous tissue, the others of white fibrocartilage. The laminae are not quite vertical in their direction, those near the circumference being curved outward and closely approximated, while those nearest the center curve in the opposite direction and are somewhat more widely separated. The fibers of each lamina are directed, for the most part, obliquely from above downward, the fibers of adjacent laminae passing in opposite directions and varying in every layer, so that the fibers of one layer are directed across those of another, like the limbs of the letter X. This laminar arrangement belongs to about the outer half of each fibrocartilage. The pulpy substance has no such arrangement, and consists of a fine fibrous matrix, containing angular cells united to form a reticular structure (Fig. 2.4).¹⁵

Bony Surfaces

Anterior surface: When viewed from front, the width of the bodies of the vertebrae is seen to increase from the second cervical to the first thoracic; there is then a slight diminution in the next three vertebrae; below this there is again a gradual and progressive increase in width as low as the sacrovertebral angle. From this point, there is a rapid diminution to the apex of the coccyx.¹⁹

Posterior surface: The posterior surface of the vertebral column presents in the median line the spinous processes. In the cervical region (with the exception of the second and seventh vertebrae), these are short and horizontal plane,

with bifid extremities. In the upper part of the thoracic region, they are directed obliquely downward; in the middle they are almost vertical; and in the lower part they are nearly horizontal. In the lumbar region, they are nearly horizontal. The spinous processes are separated by considerable intervals in the lumbar region, by narrower intervals in the neck, and are closely approximated in the middle of the thoracic region. Occasionally, one of these processes deviates a little from the median line—a fact to be remembered in practice, as irregularities of this sort are attendant also on fractures or displacements of the vertebral column.¹⁹ On either side of the spinous processes is the vertebral groove formed by the laminae in the cervical and lumbar regions, where it is shallow, and by the laminae and transverse processes in the thoracic region, where it is deep and broad; these grooves lodge the deep muscles of the back. Lateral to the vertebral grooves are the articular processes, and still more laterally the transverse processes. In the thoracic region, the transverse processes stand backward, on a plane considerably behind that of the same processes in the cervical and lumbar regions. In the cervical region, the transverse processes are placed in front of the articular processes, lateral to the pedicles and between the IV foramina. In the thoracic region they are posterior to the pedicles, IV foramina, and articular processes. In the lumbar region, they are in front of the articular processes, but behind the IV foramina (Figs. 2.5A to D).

Lateral surfaces: The lateral surfaces are separated from the posterior surface by the articular processes in the cervical and lumbar regions, and by the transverse processes in the thoracic region. They present, in front, the sides of the bodies of the vertebrae, marked in the thoracic region by the facets for articulation with the heads of the ribs. More posteriorly are the IV foramina, formed by the juxtaposition of the vertebral notches, oval in shape, smallest in the cervical and upper part of the thoracic regions, and gradually increasing in size to the last lumbar.¹⁹ They transmit the spinal nerves and are situated between the transverse processes in the cervical region, and in front of them in the thoracic and lumbar regions.

Anatomy of Muscles and Ligaments

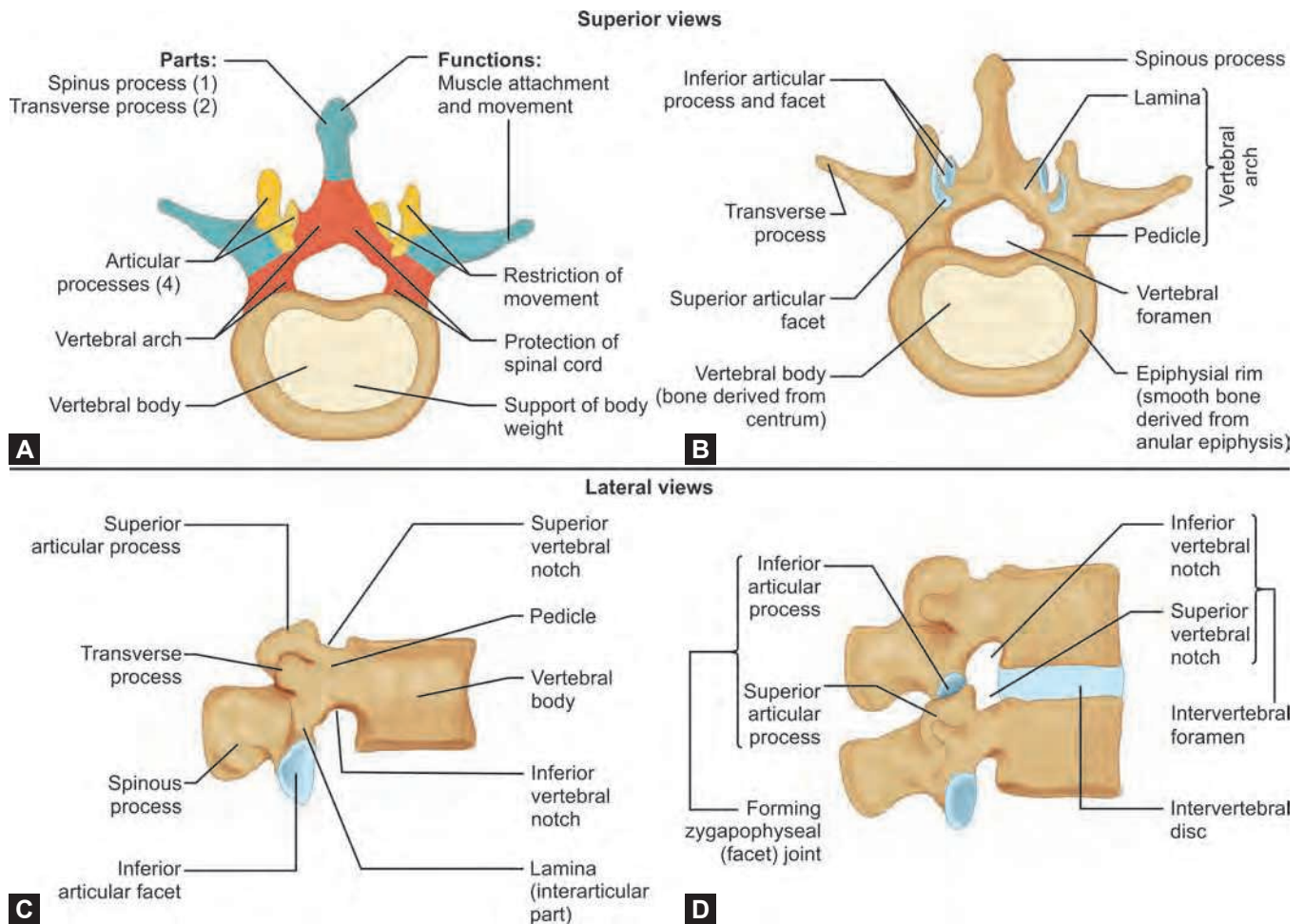
The lumbar vertebral column is supported by many large muscle groups and spinal ligaments that act to stabilize movement and maintain upright posture.^{18,19} The muscles belong to three groups, intertransverse, anterolateral, and posterior, each with many individual muscles with varying

functions. Additionally, abdominal muscles function to flex the spine, increase intra-abdominal pressure, and support the internal organs. The spinal ligaments function to prevent excessive flexion of the lumbar spine, and for this purpose are primarily arranged posterior to the center of sagittal plane rotation.¹⁸ Other muscles like the trapezius and latissimus dorsi in the back are associated with movement of the neck and shoulder.

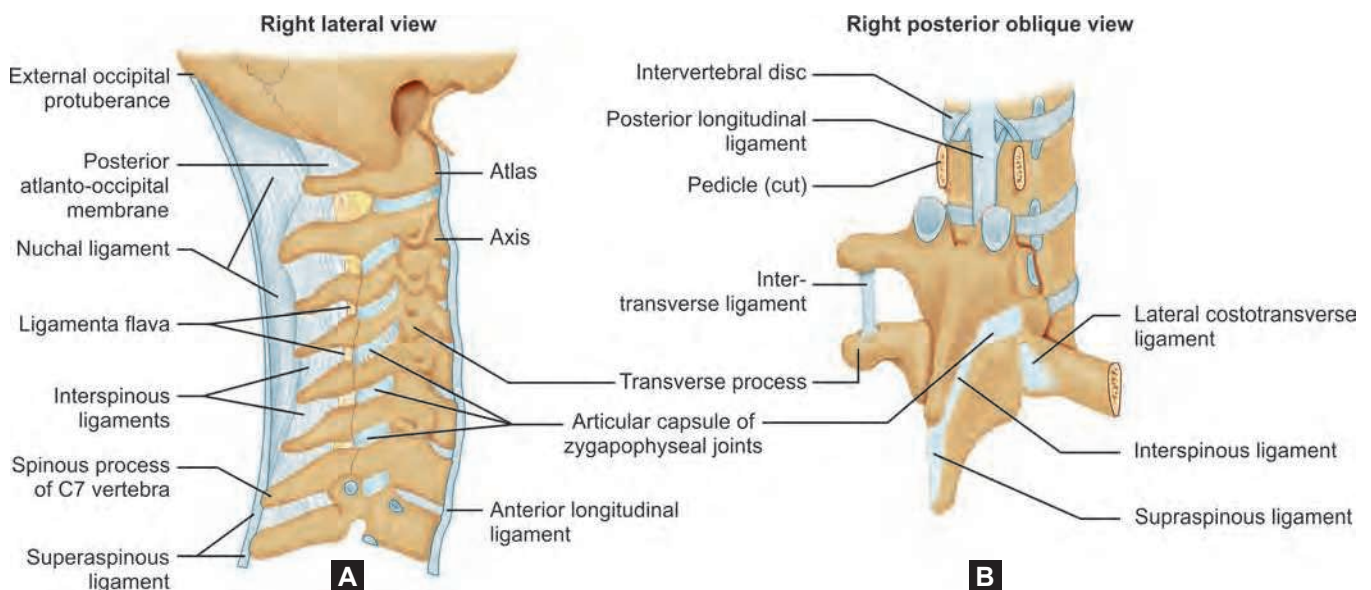
The integrity of back muscles provides support for the head and trunk of the body, strength in the trunk of the body as well as a great deal of flexibility and movement. The upper back has the most structural support with the ribs firmly attached to the thoracic spine; the lower back has the greatest flexibility allowing both flexion and extension.

The longus colli muscle is situated on the anterior surface of the vertebral column, between the atlas and the third thoracic vertebra. It is broad in the middle, narrow and pointed at either end, and consists of three portions, a superior oblique, an inferior oblique, and a vertical. The superior oblique portion arises from the anterior tubercles of the transverse processes of the third, fourth, and fifth cervical vertebrae and, ascending obliquely with a medial inclination, is inserted by a narrow tendon into the tubercle on the anterior arch of the atlas.¹⁹ The inferior oblique portion, the smallest part of the muscle, arises from the front of the bodies of the first two or three thoracic vertebrae, and, ascending obliquely in a lateral direction, is inserted into the anterior tubercles of the transverse processes of the fifth and sixth cervical vertebrae. The vertical portion arises, below, from the front of the bodies of the upper three thoracic and lower three cervical vertebrae, and is inserted into the front of the bodies of the second, third, and fourth cervical vertebrae (Figs. 2.6A and B).¹⁹

The psoas major is a long fusiform muscle located on the side of the lumbar region of the vertebral column and brim of the lesser pelvis. It joins the iliacus muscle to form the iliopsoas. In <50% of human subjects, the psoas major is accompanied by the psoas minor. On the lumbar spine, unilateral contraction bends the trunk laterally, while bilateral contraction raises the trunk from its supine position. It forms part of a group of muscles called the hip flexors, whose action is primarily to lift the upper leg toward the body when the body is fixed or to pull the body toward the leg when the leg is fixed. Due to the frontal attachment on the vertebrae, rotation of the spine will stretch the psoas. Tightness of the psoas can result in lower back pain by compressing the lumbar discs.



Figs. 2.5A to D: Surface anatomy of the vertebrae.



Figs. 2.6A and B: Ligamentous structures of cervical (A) and thoracic (B) spines.

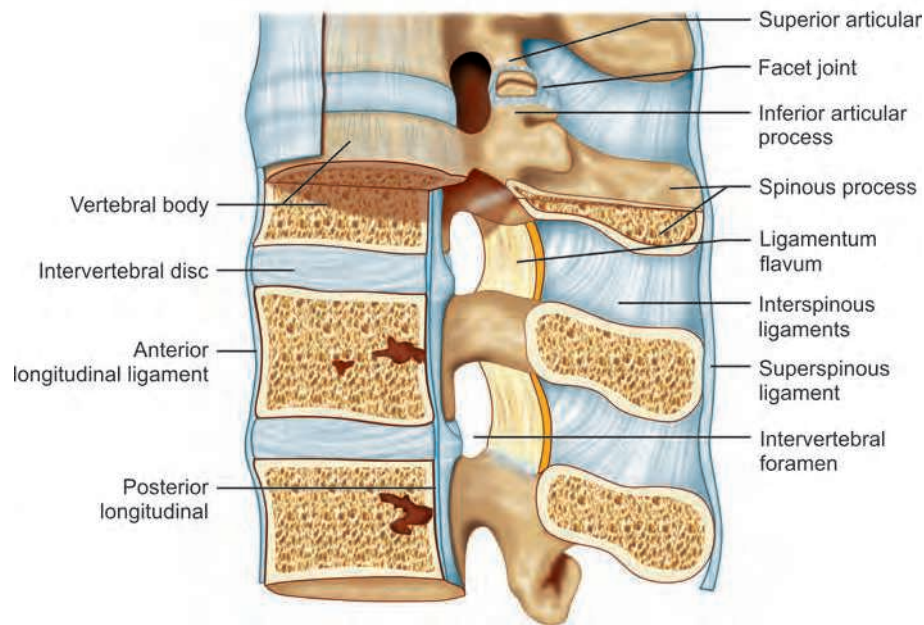


Fig. 2.7: Ligamentous structures of lumbar spine.

The IV discs and facet joints provide the spine with stability as they tie the 24 vertebrae together into a coherent whole, at the same time bestowing mobility and permitting each vertebra to move on its neighbors.

The spinal ligaments work in much the same manner. They not only play a crucial role in preventing the spine from collapsing, but they also allow movement within a predetermined range, winding up like springs in the process, and storing elastic energy that can then be used to return the spine to its previous posture.

The spinal ligaments all come together to form a continuous, dense connective tissue around the spine—a stocking that then reaches out to the entire body, connecting the vertebral column and its contents with the torso, head, limbs, and sacrum.

The spinal ligaments consist of:

- The anterior longitudinal ligament that runs from the base of the skull along the front of each vertebral body and disc and down the anterior sacrum. It fuses with the periosteum that wraps tightly around each vertebra. This ligament is the only spinal ligament that resists backward bending and limits the forward curve of the neck and lumbar regions.
- The posterior longitudinal ligament that also melds with the periosteum of the vertebral bodies and skull, but this time posteriorly. It runs along the dorsal aspect of the vertebral bodies and discs and down into the canal that lies within the sacrum. It offers attachment

sites for the dural sac of the spinal canal. It tightens with forward bending.

- The facet joint capsule, a balloon-like structure that wraps around each facet joint. Its sensory receptors likely guide the movement between adjacent vertebrae.
- The ligamentum flavum that connects the back of the vertebral arches and forms the back wall of the spinal canal. It is known as the yellow ligament because of the color imparted by the preponderance of elastic fibers. Off to the sides, it fuses with the facet joint capsules. In the midline, it turns posteriorly to become the interspinous ligament. Lengthened by flexion of the spine, its elastic fibers supply a strong returning force. The area of the spine with the most flexion, the lumbar region, is where the ligamentum flavum is the thickest.
- The interspinous ligament running between the spinous processes. Its more anterior fibers are rich in elastin and blend with the ligamentum flavum; the more posterior fibers meld with the supraspinous ligament. The interspinous ligament and (especially) the ligamentum flavum control for excessive flexion and anterior translation.²⁰⁻²²
- The intertransverse ligaments that bind the ends of the transverse processes and resist side bending to the opposite side.
- The supraspinous ligament that connects the tips of the spinous processes and goes on to meld with the thoracolumbar fascia as well (Fig. 2.7).

ANATOMY OF NEUROLOGIC STRUCTURE

The nervous system is the most complicated and highly organized of the various systems that make up the human body. It is the mechanism concerned with the correlation and integration of various bodily processes and the reactions and adjustments of the organism to its environment. In addition, the cerebral cortex is concerned with conscious life. It may be divided into two parts, central and peripheral.¹⁹

The central nervous system consists of the encephalon or brain contained within the cranium, and the spinal cord lodged in the vertebral canal; the two portions are continuous with one another at the level of the upper border of the atlas vertebra.

The peripheral nervous system consists of a series of nerves by which the central nervous system is connected with the various tissues of the body. For descriptive purposes, these nerves may be arranged in two groups, cerebrospinal and sympathetic. This arrangement, however, is an arbitrary one, since the two groups are intimately connected and closely intermingled. Both the cerebrospinal and sympathetic nerves have nuclei of origin (the somatic efferent and sympathetic efferent) as well as nuclei of termination (somatic afferent and sympathetic afferent) in the central nervous system.

The medulla spinalis, or spinal cord, forms the elongated, nearly cylindrical, part of the central nervous system that occupies the upper two-thirds of the vertebral canal. Its average length in the male is about 45 cm, in the female about 42–43 cm, while its weight amounts to about 30 g. It normally extends from the level of the upper border of the atlas to either the lower border of the first or upper border of the second lumbar vertebra. Above, it is continuous with the brain; below, it ends in a conical extremity, the *conus medullaris*. A delicate filament, the *filum terminale*, descends from the apex of the *conus* as far as the first segment of the coccyx.

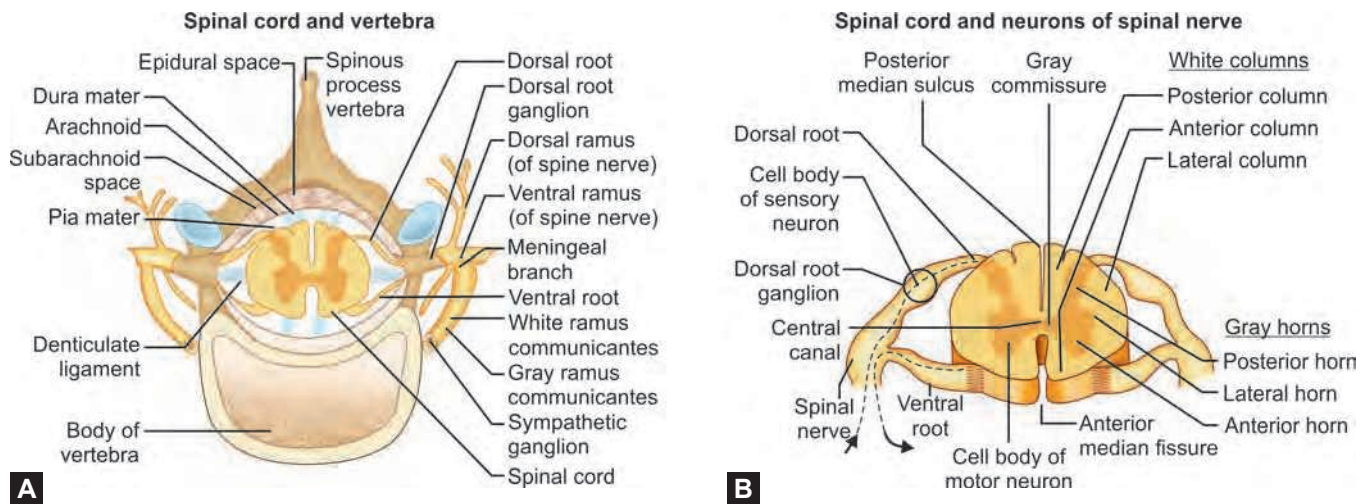
Thirty-one pairs of spinal nerves spring from the medulla spinalis, each nerve having an anterior, or ventral, root and a posterior, or dorsal, root. The dorsal root has an oval swelling, the spinal ganglion, which contains numerous nerve cells. Each root consists of several bundles of nerve fibers, and at its attachment extends for some distance along the side of the spinal cord. The pairs of spinal nerves are grouped as follows: eight cervical, 12 thoracic, five lumbar, five sacral, one coccygeal. For convenience of

description, the medulla spinalis is divided into cervical, thoracic, lumbar, and sacral regions, corresponding with the attachments of the different groups of nerves. Although no transverse segmentation is visible on the surface of the spinal cord, it is convenient to regard it as being constructed of a series of superimposed spinal segments or *neuromeres*, each of which has a length equivalent to the extent of attachment of a pair of spinal nerves. Since the extent of attachment of the successive pairs of nerves varies in different parts, it follows that the spinal segments are of varying lengths; thus, in the cervical region they average about 13 mm, in the mid-thoracic region about 26 mm, while in the lumbar and sacral regions they diminish rapidly from about 15 mm at the level of the first pair of lumbar nerves to about 4 mm opposite the attachments of the lower sacral nerves.

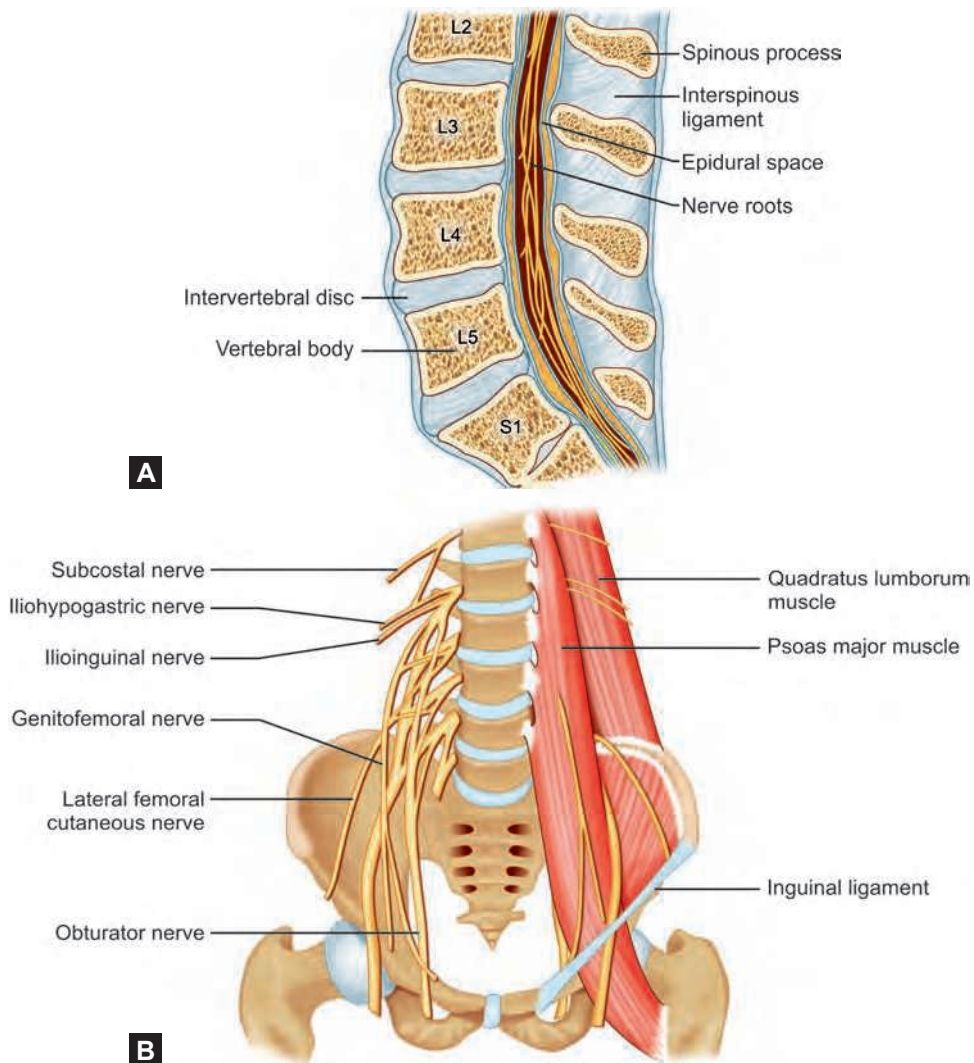
The typical spinal nerve is formed by the combination of nerve fibers from the dorsal and ventral roots of the spinal cord. The dorsal roots carry afferent sensory axons, while the ventral roots carry efferent motor axons. The spinal nerve emerges from the spinal column through IV foramen. This orientation is true for all spinal nerves except for the first spinal nerve pair, which emerges between the occipital bone and the atlas. As a result, the cervical nerves are numbered by the vertebra below, except C8, which exists below C7 and above T1. The thoracic, lumbar, and sacral nerves are then numbered by the vertebra above. In the case of a lumbarized S1 vertebra (L6) or a sacralized L5 vertebra, the nerves are typically still counted to L5 and the next nerve is S1 (Figs. 2.8 and 2.9).

Outside the vertebral column, the nerve divides into branches. The dorsal ramus contains nerves that serve the dorsal portions of the trunk carrying visceral motor, somatic motor, and somatic sensory information to and from the skin and muscles of the back. The ventral ramus contains nerves that serve the remaining ventral parts of the trunk and limbs and carrying visceral motor, somatic motor, and sensory information to and from the ventrolateral body surface, structures in the body wall, and the limbs.

The anterior divisions of the lumbar, sacral, and coccygeal nerves form the lumbosacral plexus, the first lumbar nerve being frequently joined by a branch from the 12th thoracic. For descriptive purposes, this plexus is usually divided into three parts—the *lumbar*, *sacral*, and *pudendal plexuses*.^{19–24} The nerves pass obliquely outward behind the *psoas major*, or between its fasciculi, distributing filaments to it and the *quadratus lumborum*. The first three



Figs. 2.8A and B: Anatomy of the spinal cord and nerves.



Figs. 2.9A and B: (A) Lumbar spine anatomy: sagittal view. (B) Lumbar plexus.

and the greater part of the fourth are connected together in this situation by anastomotic loops, and form the *lumbar plexus*. The smaller part of the fourth joins with the fifth to form the *lumbosacral trunk*, which assists in the formation of the sacral plexus. The fourth nerve is named the *nervus furcalis*, from the fact that it is subdivided between the two plexuses (see Fig. 2.9B).

VASCULAR ANATOMY OF THE SPINE

The basic arrangement of the spinal system consists of a grid of transversely oriented segmental vessels, connected by various longitudinal channels. This simple bit of knowledge goes a long way in understanding spinal vascular anatomy.

Each vertebral body, its ribs, muscle, nerves, and dermatome, correspond to one level or segment. It is perhaps easiest to appreciate this concept at the thoracic level, where each rib, vertebral body, and other elements constitute the prototypical segment. In the early human embryo, the neural tube is initially supplied by simple diffusion. When the limits of this nutrition are reached (at about 200 μm), a primitive vascular system consisting of paired dorsal and ventral aortae (longitudinal vessels) and transversely oriented segmental arteries come into play to vascularize the developing tissue of the embryo.

As the tissue of spinal cord continues to enlarge, new longitudinal connections form between the transverse segmental arteries, most likely to facilitate distribution of blood within the vascular system. This pattern is seen throughout the body, but is somewhat easier to recognize in the vertebrospinal arterial system, where it gives rise to adult anterior spinal artery and numerous extradural longitudinal segmental connections.²⁵ The same pattern of development takes place in the extra-axial, paravertebral space, where longitudinal connections between segmental arteries form a multitude of adult vessels, such as the vertebral, prevertebral, pretransverse, deep cervical, lateral spinal, and other arteries.

The basic arterial *vertebrospinal* vascular unit consists of two segmental vessels, left and right, arising from the dorsal surface of the aorta. The vessel curves posterolaterally in front of the vertebral body, and sends small branches into its marrow. In front of the transverse process, the segmental artery bifurcates into a dorsal branch and an intercostal branch. The intercostal segment provides blood supply to the rib and adjacent muscle and other tissues. The dorsal branch feeds the posterior elements

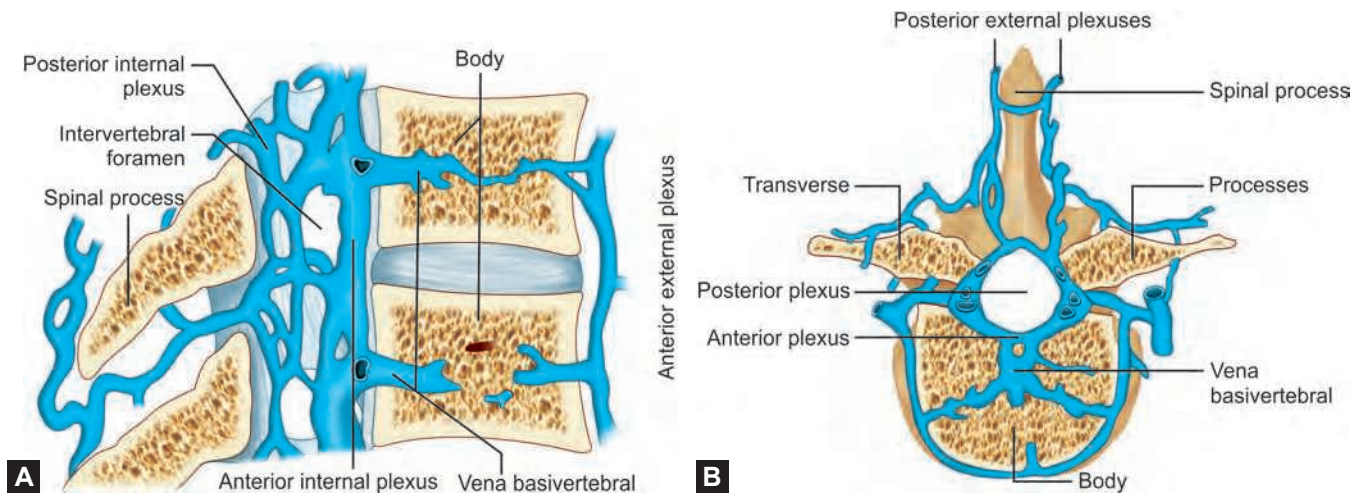
and, via the neural foramen, sends branches to supply the local epidural and dural elements, as well as a radicular artery to nourish the nerve root.

At some levels, the radicular artery is enlarged because it maintains its embryonic access to the anterior spinal artery. At this level, the artery is called “radiculomedullary” because it also supplies a large segment of the spinal cord.

The system varies in the cervical, upper thoracic, and sacral segments (i.e. exceptions are greater than the rule), but the basic principle of segmental dural and radicular vessels supplying neural tube elements is a very useful guide. Variation comes most often in the form of segmental vessel origin. The descending aorta provides blood supply for most thoracic and lumbar segments; the vertebral artery, the subclavian branches (costocervical trunk, for example), supreme intercostal artery, and the median sacral artery (effectively a diminutive continuation of the aorta below the iliac bifurcation) play this role at the appropriate segments.

In the cervical spine, the left and right vertebral arteries arise off the first portion of the subclavian artery for each respective side. These arteries are generally unequal in size, with the left the larger and dominant of the two. The typical course of the vertebral artery allows for its classic division into four segments, V1 through V4. The first segment (V1) starts with the branching of the vertebral artery from the subclavian artery and follows as it travels anterior to the transverse foramen of C7 and into the transverse foramen of C6. The second segment (V2) includes the section of the artery as it passes through the successive vertebral foramina from C6 to C1. V3 comprises the portion from the superior aspect of the arch of the atlas to the foramen magnum; (V4) extends from the foramen magnum to the confluence with the contralateral vertebral artery and together they form the basilar artery. The upper cervical cord segment is supplied from the left C5/6 level, while the inferior cervical cord from the right C4/5 segment. The lower portion of the cervical anterior spinal artery is fed via the left C5/6 radiculomedullary contributor, which also happens to supply the posterior spinal artery network; the upper anterior spinal artery segment is fed by the right C4/5 radiculomedullary artery (Figs. 2.10A and B).

The artery of thoracic enlargement (*Adamkiewicz*) usually comes of T9 through T12 regions.²⁶ There is often a region of the thoracic cord (depending on the level of the Adamkiewicz origin) that is rather small in caliber, relative to the more well-developed cervical region vessel.



Figs. 2.10A and B: (A) Sagittal and (B) axial views of venous system of the vertebra.

A “watershed” of sorts therefore exists that occasionally may correspond to cord infarction in states of hypotension. The Artery of Adamkiewicz can occasionally (25% of the time) come off unusually high or low.

The terminal region of the cord, *conus medullaris*, is quite vascular. It is usually visualized as an arterial “basket,” consisting of the anterior spinal artery and two “posterior” spinal arteries, which are anastomosed at the bottom of the conus. Multiple radicular arteries, supplying the nerve roots of the cauda equina, are usually passed through the basket (unlike the rest of the cord, where radicular arteries are usually visualized via segmental arterial injections, and normally flow toward, rather than away, from the cord).

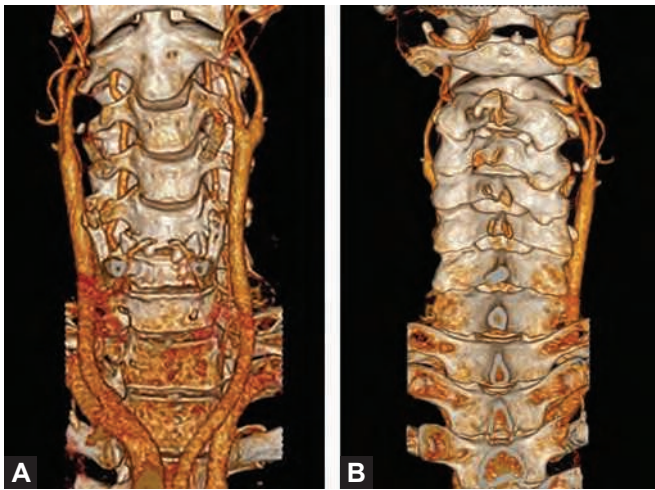
The *median sacral artery*—a continuation of the aorta,³⁰ the median or middle sacral artery usually comes off the bifurcation. As a homolog of the aorta, it gives origin to segmental vessels of the sacrum. *Lateral sacral arteries*—they are longitudinal vessels that are homologous to the paravertebral (pretransverse) anastomoses in the thoracolumbar segments and to the vertebral artery in the cervical spine. They arise from proximal internal iliac arteries.

Gilbert Breschet in 1819 provided the first detailed anatomic description of the vertebral venous plexus.²⁸ The vertebral *venous system* can be divided into three components—the intradural (extramedullary and intramedullary veins), extradural (epidural), and intraosseous /paraspinal veins. Classically, the names are anterior external, anterior internal, posterior internal, and posterior external venous plexuses, corresponding to intradural and extradural networks. The veins are a capacitance network—about 75% of intracranial blood pool at any given time is situated in

the veins. The same probably goes for the spinal cord, if not more. The intramedullary and extramedullary systems are highly redundant and therefore fail only under extreme circumstances.

The spinal cord is drained by a redundant, centripetally arranged venous network that extends to the cord surface in a semi-organized fashion. These intramedullary veins (also known as radial veins) are angiographically invisible in normal state. Once on the surface, the spinal veins are organized in a loose network that is much more distributive than the arterial system. Anterior and posterior longitudinal spinal veins are described; these run along the length of the cord in an interconnecting fashion, and go by various names such as “anterior and posterior coronal veins”; the anterior vein may pass for a discrete entity and may be called “anterior median spinal vein,” but variability is the rule.

The internal venous plexus has been extensively studied and is located within the epidural space.²⁹⁻³¹ The internal vertebral venous plexus consists of four interconnecting longitudinal vessels, two anterior and two posterior. The external vertebral plexus (EVP), in contrast, lies peripheral to the vertebrae and is made of the anterior and posterior EVPs.³² The EVP is situated anterior to the vertebral bodies and in relation to the laminae, spinous processes, transverse processes, and articular processes, respectively. These veins communicate with the segmental veins of the neck, the intercostal, azygos, and lumbar veins. With the veins of bones of the vertebral column, the internal and external EVPs form Batson’s plexus.²⁹ These veins are predominantly located in the anterolateral part of the epidural space, and



Figs. 2.11A and B: (A) AP view computed tomography (CT) angiogram showing the vertebral artery course. (B) PA view CT angiogram showing the vertebral artery course.

ultimately drain into the azygos system of veins. As the whole system is valveless, increased intrathoracic or intra-abdominal pressure can lead to major congestion and vessel enlargement within the spinal canal. The epidural venous plexus is surrounded by sparse quantity of fat. The anterior epidural space is entirely occupied by a rich venous plexus (Batson's plexus). The plexus communicates with the intracranial sigmoid, basilar venous sinuses, basivertebral vein, occipital vein, and the azygos system. The plexus is linked to the abdominal and thoracic veins by the IV foramina and through this connection transmit intra-abdominal and intrathoracic pressure to the epidural space. The rich venous plexus is also connected to the iliac veins through the sacral venous plexus (Figs. 2.11A and B).

FUNCTIONAL ANATOMY/ STRUCTURAL SPINAL STABILITY

Overview and Definition of Terms

The functional spinal unit (*FSU*) is the smallest physiological motion unit of the spine to exhibit biomechanical characteristics similar to those of the entire spine. An *FSU* consists of an inferior and superior vertebral body and all of the connective soft tissues between them.³³ Contractile and nervous tissues are excluded. When the motion of an *FSU* lies within an anatomical plane of the vertebral coordinate system, the planar motion is relatively straightforward to describe. Planar motion is often a combination

of rotation and translation. One approach to describing planar motion is to define a rotation angle and a center of rotation (*COR*). These two variables completely describe any planar motion. Throughout a range of motion, the *COR* may be fixed or may move with the degree of motion. When the motion of an *FSU* is not planar, describing the three-dimensional motion completely is nontrivial. The mechanical behavior of the *FSU* is described by the relation between the applied load and resulting motion and this relation is often nonlinear.

Range of motion is the motion that occurs between the limits of the applied load “the entire range of the physiological IV motion, measured from the neutral position.” It is divided into two parts: neutral and elastic zones.

Stiffness (*K*) is the slope of the load-motion curve (units N/mm or Nm/deg). It is important to define at which point on the curve the stiffness is calculated. Typically it is defined in the secondary region of the curve where stiffness is constant over that range.

Neutral zone is the zone of high flexibility; it is that part of the range of physiological IV motion, measured from the neutral position, within which the spinal motion is produced with a minimal internal resistance.³⁴

Motion

The movements permitted in the vertebral column are flexion, extension, lateral movement, and rotation.

The spinal muscles function to stabilize and achieve movements of the vertebral column. A number of muscle groups act on the spine. Those located anterior to the vertebral bodies act as flexors. These include longus capitis and colli, psoas major, and rectus abdominis. Lateral flexion is achieved by the scalenes in the cervical region and quadratus lumborum, transversus abdominis, and the abdominal obliques in the lumbar region. The flexors and lateral flexors of the spine are innervated by the ventral rami of spinal nerves.

In contrast, the extensors of the spine are located posterior to the vertebral bodies and are innervated by the dorsal rami of spinal nerves. The term “spinal muscles” typically refers to the extensors of the spine.

In flexion, or movement forward, the anterior longitudinal ligament is relaxed, and the IV fibrocartilages are compressed in front, while the posterior longitudinal ligament, the ligamenta flava, and the inter- and supraspinal ligaments are stretched, as well as the posterior fibers of the IV fibrocartilages. The interspaces between the laminae

are widened, and the inferior articular processes glide upward, upon the superior articular processes of the subjacent vertebrae. In general, this motion increases the cross-sectional area of the spinal canal. Flexion is the most extensive of all the movements of the vertebral column, and is freest in the lumbar region.

In extension, or movement backward, an exactly opposite disposition of the parts takes place. This movement is limited by the anterior longitudinal ligament, and by the approximation of the spinous processes. It is freest in the cervical region.

In lateral movement, the sides of the IV fibrocartilages are compressed, the extent of motion being limited by the resistance offered by the surrounding ligaments. This movement may take place in any part of the column, but is freest in the cervical and lumbar regions.

Rotation is produced by the twisting of the IV fibrocartilages; this allows a considerable extent of movement when it takes place in the whole length of the column, although only slight between any two vertebrae. The extent and variety of the movements are influenced by the shape and orientation of the zygapophyseal joint articular surfaces. Thus, facet joints can be said to act like railway tracks, guiding the movements of the spine. In the *cervical region*, the upward inclination of the superior articular surfaces allows free flexion and extension. Extension can be carried farther than flexion; at the upper end of the region, it is checked by the locking of the posterior edges of the superior atlantal facets in the condyloid fossae of the occipital bone; at the lower end, it is limited by a mechanism whereby the inferior articular processes of the seventh cervical vertebra slip into grooves behind and below the superior articular processes of the first thoracic. Flexion is arrested just beyond the point where the cervical convexity is straightened; the movement is checked by the opposition of the projecting lower lips of the bodies of the vertebrae with the shelving surfaces on the bodies of the subjacent vertebrae. Lateral flexion and rotation are free in the cervical region; they are, however, always combined. The upward and medial inclinations of the superior articular surfaces impart a rotary movement during lateral flexion, while pure rotation is prevented by the slight medial slope of these surfaces.

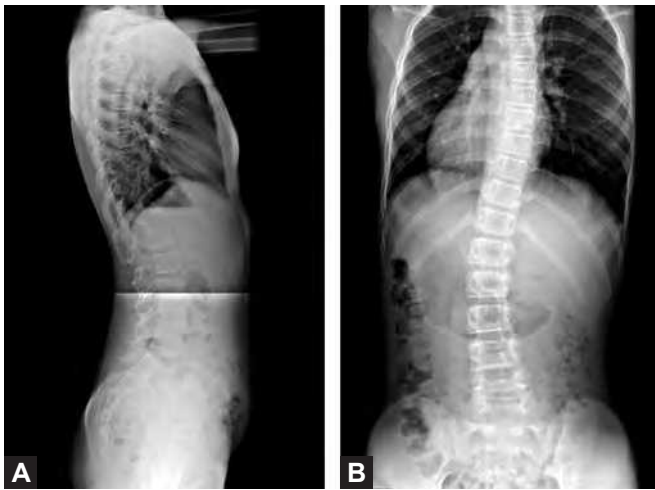
In the *thoracic region*, notably in its upper part, all the movements are limited in order to reduce interference with respiration. The almost complete absence of an upward inclination of the superior articular surfaces prohibits any

marked flexion, while extension is checked by the contact of the inferior articular margins with the laminae, and the contact of the spinous processes with one another. The mechanism between the seventh cervical and the first thoracic vertebrae, which limits extension of the cervical region, will also serve to limit flexion of the thoracic region when the neck is extended. Rotation is free in the thoracic region: the superior articular processes are segments of a cylinder whose axis is in the mid-ventral line of the vertebral bodies. The direction of the articular facets would allow of free lateral flexion, but this movement is considerably limited in the upper part of the region by the resistance of the ribs and sternum.

In the *lumbar region*, flexion and extension are free. Flexion can be carried farther than extension, to just beyond the straightening of the lumbar curve; it is, therefore, greatest at the lowest part where the curve is sharpest. The inferior articular facets are not in close apposition with the superior facets of the subjacent vertebrae, and on this account a considerable amount of lateral flexion is permitted. For the same reason, a slight amount of rotation can be carried out, but this is so soon checked by the interlocking of the articular surfaces that it is negligible, and that is why the axis of rotation of a lumbar vertebra lies close to the base of the spinous process.

Spinal Stability

It is the most clinically important biomechanical parameter, but also the most elusive. From an engineering perspective, a system is said to be stable if it returns to its initial state after a perturbation. With an axial compressive load of >20 lbs, the ligamentous lumbar spine is unstable; it cannot remain upright and buckles. Thus, the musculature of the spine is essential in maintaining spinal stability. Leonardo da Vinci was the first bioengineer to appreciate this instability and hypothesized that the musculature of the spine performed in the same way as the guy wires of a ship's mast. White and Panjabi, in their text, provided a more clinical definition of spinal stability: "the ability of the spine under physiological loads to limit patterns of displacement so as not to damage or irritate the spinal cord or nerve roots and, in addition, to prevent incapacitating deformity or pain due to structural changes..." There are quantitative guidelines that are typically specific measurements, beyond which the spine is felt to be unstable. Many of these will be further discussed in the pertinent chapters to follow.



Figs. 2.12A and B: (A) Standing sagittal view of the spine. (B) Standing coronal view of the spine.

Spinal Balance

The concept of spinal balance is based upon the principle that overall function and upright posture is most efficient when the skull, and the rest of the upper body mass, is centered over the pelvis. Dubousset described this concept as the “cone of balance” or cone of economy.³⁸

In the coronal plane, this effect is achieved through body symmetry. In order to achieve the same effect in the sagittal plane, the spine presents several closely related curves, which correspond to the different regions of the spinal column, and are called cervical, thoracic, lumbar, and pelvic. Curves that are convex ventral are described as lordotic curves, and curves that are convex dorsal are described as kyphotic (Figs. 2.12A and B). The *cervical* curve, which is normally lordotic, begins at the apex of the odontoid process, and ends at the middle of the second thoracic vertebra; it is the least marked of all the curves. The *thoracic* curve, which is kyphotic, begins at the middle of the second and ends at the middle of the 12th thoracic vertebra. Its most prominent point behind corresponds to the spinous process of roughly the seventh thoracic vertebra. The *lumbar* curve is more marked in the female than in the male; it begins at the middle of the last thoracic vertebra, and ends at the sacrovertebral angle. It is lordotic, the convexity of the lower three vertebrae being much greater than that of the upper two. The *pelvic* curve begins at the sacrovertebral articulation, and ends at the point of the coccyx; its concavity is directed downward and forward. The thoracic and pelvic curves are termed primary curves, because they alone are present during fetal life. The cervical and lumbar

curves are compensatory or secondary, and are developed after birth, the former when the child is able to hold up its head (at 3 or 4 months), and to sit upright (at 9 months), the latter at 12 or 18 months, when the child begins to walk.

The vertebral column has also a slight *lateral* curvature, the convexity of which is directed toward the right side. This may be produced by muscular action in right-handed individuals, especially in making long-continued efforts, when the body is curved to the right side. In some patients who are left-handed, the convexity aims to the left side. A competing theory suggests that this curvature is produced by the aortic arch and upper part of the descending thoracic aorta—a view that is supported by the fact that in cases where the viscera are transposed and the aorta is on the right side, the convexity of the curve is directed to the left side.

The degree to which the spinal balance is assigned in reference to the sagittal plane is defined as the plumb line and its relationship to axis of rotation about the hip; this concept makes assessment of both hip positions on the standing sagittal film very important. Ideal balance is referred to as a plumb line from the center of C7 to within 2 cm from the posterior superior aspect of the sacrum.

Pelvic parameters include pelvic incidence (PI), sacral slope (SS), and pelvic tilt (PT). *Pelvic incidence* is defined as the angle between the perpendicular to the sacral endplate at its midpoint and the line from that point to the midpoint of femoral head axis. It is clinically relevant for its correlation to the optimal lordosis ($PI \approx LL + 9^\circ$). *Sacral slope*: angle between the sacral endplate and the horizontal. *Pelvic tilt*: angle between the line connecting the midpoint of the sacral endplate to the femoral head axis and the vertical. The PI is equal to the sum of the SS and the PT (Fig. 2.13).^{35,36}

Thoracic kyphosis is measured from the superior endplate of T4 to the inferior endplate of T12. *Lumbar lordosis* is measured from the superior endplate of L1 to the superior endplate of S1.

While significant debate exists about how to best define ideal global spinal balance, it is determined by the thoracic kyphosis, the lumbar lordosis, their relationship to each other, and the PI at the base of the spine. While neither normative values for ideal cervical lordosis in the adult population, nor the best parameters for defining cervical alignment have been clearly identified, a growing body of evidence suggests that balance in this portion of the spine, too, contributes to both global spinal balance and overall function.³⁹

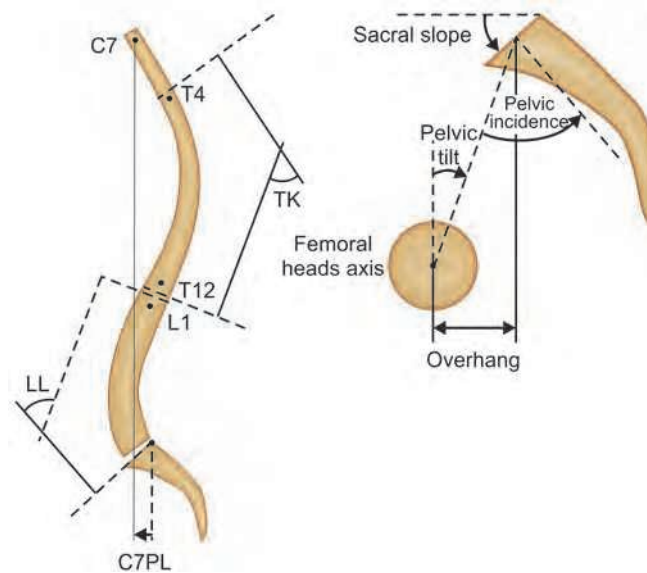


Fig. 2.13: Spinopelvic parameters.

CONCLUSION

The spinal column serves several functions: protect the neural elements, provide upright structure, and allow enough mobility for locomotion and interaction with our environment. The structure needed to achieve both these complimentary and contradictory missions results in a highly complex entity. The anatomic relationships described here play a critical role in normal and pathologic states of the spine, and in the surgical and nonsurgical management of these states.

KEY POINTS

- Anatomy of the spine
- Spine development
- Vascular and neurological anatomy
- Spine anatomy and stability
- Functional spine anatomy

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Clinical Biomechanics of the Spine

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Snapshot

- » History
- » Spinal Anatomy
- » Biomechanics of the Spine
- » Trauma

HISTORY

The biomechanics of the spine have been researched and written about for thousands of years to answer questions about how and why we move and become injured. The first documented appreciation for the spine and spinal anatomy was from the ancient Egyptians. Due to their in-depth knowledge of the process of mummification, they possessed a basic understanding of the spine and associated connections in the body. In the ancient papyrus that Edwin Smith brought to England, there were descriptions from 1700 BCE of head and spine diseases in 48 patients detailing examination, diagnosis, and treatment.¹

The *Iliad*, written by Homer around 700 BCE, was the next surviving text to relate an appreciation of spinal cord injury. When Hector was killed during the Trojan War after a sword pierced him in the neck, Homer described him as going limp. The story was referring to an injury to his spinal cord causing paraplegia.² Later, Hippocrates, who lived in 400 BCE and wrote about the spine, discovered basic methods for biomechanical corrections of deformities, including simple rope and weight devices. Through extensive studies, he also divided the spine into three separate parts: above the clavicle, at the chest level, and below the chest.²

During 1000 CE, Avicenna was a Persian anatomist and philosopher who made great contributions to the study of spinal biomechanics. In *The Book of Healing*, he developed

an elaborate theory of motion. As a physician, he studied the spine in great detail and came to understand the mechanical movements between the skull and spine.³ He also wrote about the anatomy of the nervous system, although this work was mainly Galenic in origin.⁴ In the late 1400s, Leonardo da Vinci, the great scientist, painter, and inventor, performed extensive research and completed the first anatomically correct sketches of the spine. He acquired a detailed understanding of biomechanics and described an analogy likening the spinal column to the mast of a ship.⁵

Shortly thereafter, in the 1600s CE, Giovanni Borelli published the first extensive report linking the structure of the spine to the functional mechanics of movement. Through investigations of the connections between muscles and joints, he was able to calculate the center of gravity of the human body. As a result of his integration of biology with mechanical properties, he is commonly referred to as the “Father of Biomechanics.”⁶

During the 1800s and 1900s, great advances were made when hanging became the preferred method of exacting justice. This common practice led to a better understanding of the biomechanical stresses and fractures related to injuries to the spine and spinal cord. Later in the 20th century, with the explosion of advanced physics, modern medicine, and computer technology, the knowledge of the spine and the body as a whole has grown exponentially.

SPINAL ANATOMY

The spine is a structure of bone and cartilage consisting of vertebrae connected by intervertebral discs and closely related nerves, veins, arteries, and lymphatic vessels. The 33 vertebrae are divided into four groups based on their location and physical properties. From cephalad to caudal, there are seven cervical vertebrae (C1–C7), 12 thoracic vertebrae (T1–T12) that are supported by connections to the rib cage, five lumbar vertebrae (L1–L5), and five sacral and four coccygeal vertebrae that are fused and immobile.⁷

These regions normally exhibit distinct forms of curvature. The cervical and lumbar regions have a primary lordotic curve, with the concavity posteriorly, while the thoracic and sacral spinal vertebrae make up a kyphotic curve, in which the concavity is located anteriorly. This undulating pattern of alternating curve directions is best demonstrated when standing erect, and helps the body assume various positions such as sitting and lying down (Fig. 3.1).⁸

Functional Unit of the Spine

The functional unit of the spine consists of two bony vertebrae and the cartilaginous disc between them, as well as the adjoining ligaments. Also termed a motion segment, this combination of bone and fibrocartilage functions as a unit and exhibits the characteristic biomechanics of the entire spine. Although closely associated with muscle, nerves, and vessels, these structures are not considered a part of the biomechanical functional unit.⁸

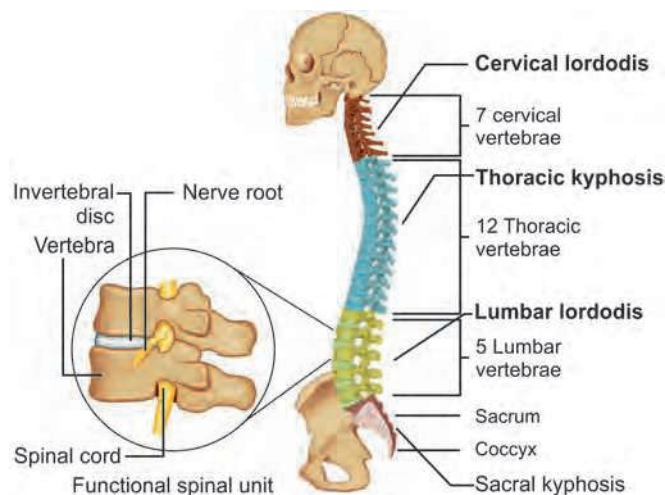


Fig. 3.1: Spinal functional unit and curvature.

Bone

The bony part of the spine is called the vertebra. The vertebrae are typically described as comprising multiple distinct parts. The largest part, the body, is the weight-bearing portion of the spine and is attached to the cartilaginous discs. Attached posteriorly is the vertebral arch, a thin, strong structure consisting of the pedicles, transverse processes, and lamina, with the singular spinous process protruding posteriorly. This arch forms the vertebral foramen that can be thought of as a hollow canal that protects the spinal cord (Fig. 3.2).⁹

Disc

The intervertebral disc connects two vertebral bodies. This cartilage-like component serves an essential role as a shock absorber for the human body and makes possible the range of motion of the spine. There are two main parts of the disc. The first is the inner nucleus pulposus, which consists of a gelatinous substance of collagens and normally water-laden glycosaminoglycans, and serves the purpose of absorbing most of the axial energy. Surrounding and containing this is the annulus fibrosis, a thicker fibrous layer composed primarily of collagen fibers.^{10,11}

Ligaments and Tendons

Tendons and ligaments connect muscle to bone and bone to bone, respectively, and enable the musculature to move our bodies. Ligamentous and tendinous connections permit motion of spinal joints and augment the overall strength and stability of the spine. The anterior longitudinal ligament runs along the entire length of the spinal column and is attached to the anterior aspect of each vertebra and disc

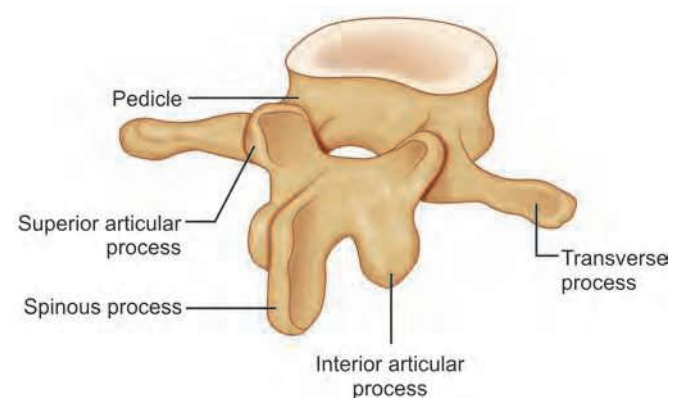


Fig. 3.2: Anatomy of a spinal vertebra.

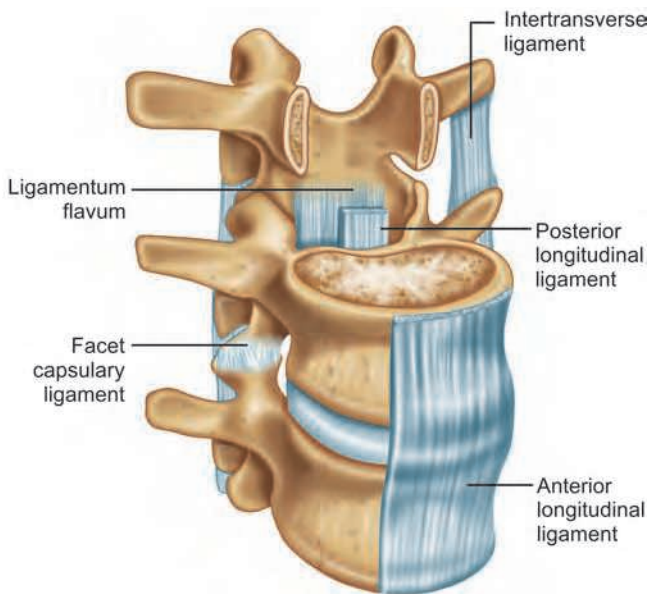


Fig. 3.3: Anatomy and structure of spinal column ligaments.

(Fig. 3.3). The posterior longitudinal ligament also spans the entirety of the spinal column, posterior to the discs and vertebral bodies. On the posterior arch, the laminae are each linked by individual ligamentum flavum. These ligaments collectively serve to protect the spinal cord while permitting movement of the spine. By serving as a check-rein once a maximum tension in the direction of their fibers has been reached, ligaments prevent hypermobility of the vertebral canal, thereby protecting the spinal cord and spinal nerves.⁸⁻¹⁰

BIOMECHANICS OF THE SPINE

The spine is a highly complex biomechanical structure that can be described using a combination of simple fundamental biomechanics as well as more complex functional biomechanics. In addition, each region of the spine is unique in its biomechanical properties.

Fundamental Biomechanics

Physics

A firm grasp of the physical sciences is important for comprehending the biomechanical properties of the human body, and for this reason the following few concepts are indispensable. An appreciation for momentum, Newton's first and second laws, and Hooke's law contributes to a more fundamental understanding of the mechanical properties of the spine.⁹

Momentum and Force

Momentum is the product of the scalar quantity mass and the vector quantity velocity. An appreciation for the effect of momentum on biomechanics can be better related through Newton's first law, which states that an object at motion will stay at motion until acted upon by an outside force. Physical entities within the spine are able to provide the reactive force necessary to maintain the spine in a stable position. Newton's second law states that the net force vector of an object is equal to the product of the scalar mass and the net acceleration vector. This explains that, although many forces may be acting on a single object, all of the vector forces can be combined into a resultant force vector. Newton's third law holds that for every force there is an equal and opposite reaction force. The internal mechanistic properties of the spine must equal and withstand any external force applied, or there will be a rupture, or break in a spinal element.⁹

Hooke's Law

Hooke's law is of great importance in relation to biomechanics. This tenet holds that when a force or stress is applied to an object, there is a degree of deformation or strain on that object when within the elastic zone. This concept can be extended and graphically represented with a stress-strain curve, describing the biomechanical properties and possible deformation capability. The curve starts with a neutral zone in which stress is applied, yet no deformation is observed. This is due to energy being dissipated from one part of the body into others, such as from the vertebra to the adjacent soft tissues. After exceeding the neutral zone, the elastic zone is reached, in which the extent of deformation of the entity is proportional to the strain applied. According to Hooke's law, the stress-strain curve for the elastic zone should be linear in nature, and it is referred to as elastic because once the strain is removed, the shape returns to its neutral state. However, this law further holds that the deformation of an entity can reach a critical level, in which deformation is no longer elastic, and permanent or "plastic" deformation is incurred.⁹ This is often observed clinically when a patient presents with joint laxity or hypermobility of a skeletal segment.

Force and Movement Definitions

Types of forces: The spine is a robust structure that can withstand a multitude of complex forces, and each type

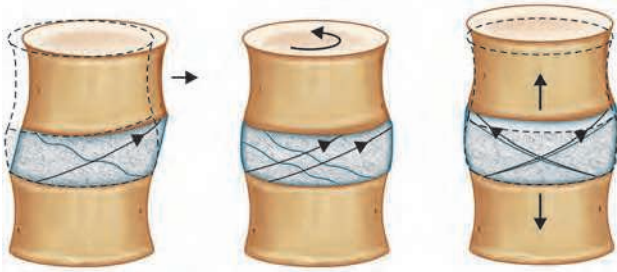


Fig. 3.4: Represents different forces that can be applied to the spinal column including shear, torsion, and tension.

of force may result in a different reaction. At any one time there may be multiple forces acting upon the spine, and what a person feels is the combined resultant force.¹¹ The four basic forces are torsion, tension, compression, and shear forces. The biomechanical properties of the spine and all contributing anatomy provide for great resistance to these influences (Fig. 3.4).^{8,10}

Coupling motion: Motion coupling is a phenomenon that is demonstrated throughout the human body and the spine is no exception. Coupling occurs when one type of motion induces a compensatory motion in a different plane along a different axis. The intended movement is referred to as the main motion, while the secondary movement is the coupled motion. This is an important biomechanical concept, especially important in the spine because it illustrates how spinal anatomy functions when in motion, and how forces move through the spine.^{8,12}

Each part of the spine has unique geometry, and the coupling patterns differ between the cervical, thoracic, and lumbar regions. The best example of coupling occurs in the cervical spine. When the cervical region bends, there is resultant coupling and secondary cervical rotation to the opposite lateral side.^{8,13} Coupling in the lumbar spine occurs during side bending as well. Similar to the cervical spine, side bending is coupled with axial rotation; however, in the lumbar region, rotation is in the same direction as side bending. The upper thoracic spine exhibits this side-bending-rotational-coupling phenomenon similar to the cervical region, while the lower thoracic spine displays very little coupling.^{8,11,14}

Functional Biomechanics

Range of Motion and the Neutral Zone

The spine exhibits a nonlinear load displacement curve. This curve can be seen as two separate and distinct regions

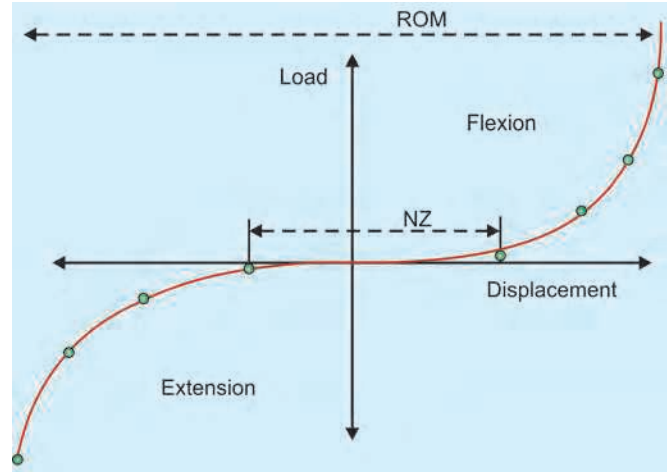


Fig. 3.5: Graph is displaying displacement vs load for the full range of motion (ROM) of the spine. As demonstrated, the neutral zone is the area of low load and resistance on the spine. The area beyond the neutral zone, but still within the ROM, is known as the elastic zone.

with unique qualities—the neutral zone and the elastic zone. The neutral zone is the arc in which the spine exhibits the maximum flexibility with minimal increase in tension, and corresponds to the initial range of motion. The spine experiences relatively low stresses within the neutral zone. The second portion of the load displacement curve is the elastic zone. This is reached when the motion causes the spine to move beyond the neutral zone of least resistance. The elastic zone encompasses the limits of range of motion and the anatomy is subject to much higher internal resistance (Fig. 3.5).^{15,16}

If the neutral zone were to be expanded, there would be increased laxity (ligamentous, muscular, etc.) in motion segments and the elastic zone would be relatively smaller. Having a smaller elastic zone would increase the demands on the stabilization system of the spine. The stabilization of the spine is comprised of the anatomical structures contributing to passive, active, and neutral support. If the neutral zone was larger, the stresses exerted on the body due to internal resistance would increase greatly. This increase would ultimately bring about instability due to the increase in internal forces over a smaller range of motion. The neutral zone appears to be a clinically important measure, and some studies have shown that the size of the neutral zone may be a better indicator of spinal instability than the total range of motion.¹⁷ The neutral zone may be increased by weakness of the paraspinal muscles, or with injury, and decreased by surgical fixation or through processes such as osteophyte formation.¹⁵

Table 3.1: Cyclic loading with various loads increases the rate of failure of the lumbar spine.

	Relative load (%)		Number of loading cycles		
	10	100	500	1000	5000
60–70	10%	55%	80%	95%	100%
50–60	0%	40%	65%	80%	90%
40–50	0%	25%	45%	60%	70%
30–40	0%	0%	10%	20%	25%
20–30	0%	0%	0%	0%	10%

Source: Vaccaro AR, Betz RR, Zeidman SM. Principles and Practice of Spine Surgery. Philadelphia, PA: Mosby; 2003.

Cortical Shell

The cortex is a thin layer of compact, hard bone surrounding the porous trabecular bone of the vertebral body. Although only a small portion of the total vertebral body, the cortex exhibits certain biomechanical properties that make it very important for spinal function. With advances in technology, computed tomography scans of vertebral bodies have enabled finite element analysis experimental models to be constructed and used to predict failure loads and fracture patterns.¹³ One such model was axially loaded to the failure point, and found a wide variation in the load-bearing capacity of the cortical shell, supporting anywhere from 12% to 75% of the total compressive load.^{18,19}

Regional Biomechanics

Cervical Spine

The cervical spine is unique in that, while one end is connected to the spine below, the other end articulates with the skull. The cervical spine is associated with the most mobility of any region, and this is due to a combination of flexion/extension, axial rotation, and lateral bending capabilities. In particular, the occiput-C1 articulation has the greatest combined flexion extension capacity with 25° total motion. The C1–C2 articulation accounts for approximately 40° of axial rotation, nearly half of the total rotation for the entire cervical region. The mid-cervical joints permit the greatest lateral movement of the spine as well. The relative paucity of structural support and constraints to motion in the cervical region allows for a high degree of mobility, but also makes the cervical spine especially vulnerable to destabilizing injuries (Table 3.1).⁷

Thoracic Spine

Although one of the strongest and most stable parts of the spine, the thoracic spine exhibits a relatively limited

range of motion due to the articulations with the ribs. The axial rotation of the upper thoracic region is significantly greater than the lower thoracic region. In addition, the thoracic spine is biomechanically unique in that the degree of possible side bend is roughly equivalent for each vertebral level (Table 3.1).⁷

Lumbar Spine

Situated at the caudal end of the spine, the lumbar spine must support the entire load from above. This section is comprised of the five largest vertebrae in the human body, and the increased diameter helps to distribute the force of this large portion of bodyweight.⁷ The lumbar region exhibits relatively less mobility than the cervical region and more than the thoracic. One unique biomechanical feature of the lumbar spine is the very limited rotational capability. This is because, in contrast to the cervical region, the lumbar spine has facet joints oriented in the sagittal plane, which restrict axial rotation (Table 3.1).

TRAUMA

The amount of tissue damage is a direct result of the direction, magnitude, and temporal qualities of the forces applied. According to Herkowitz et al.,⁸ there are three main types of pathological loadings of the spine. Each type results in a unique and specific response and causes varying degrees of damage. The first and most common type is acute trauma, which describes a situation in which one force is able to surpass the load-bearing capabilities of the tissue leading to injury. The second type is cumulative trauma, a gradual weakening of the tissue capacity due to repetitive loading. The final type is instability, defined as abnormal displacement of a spinal segment leading to pain.⁸

Acute Trauma

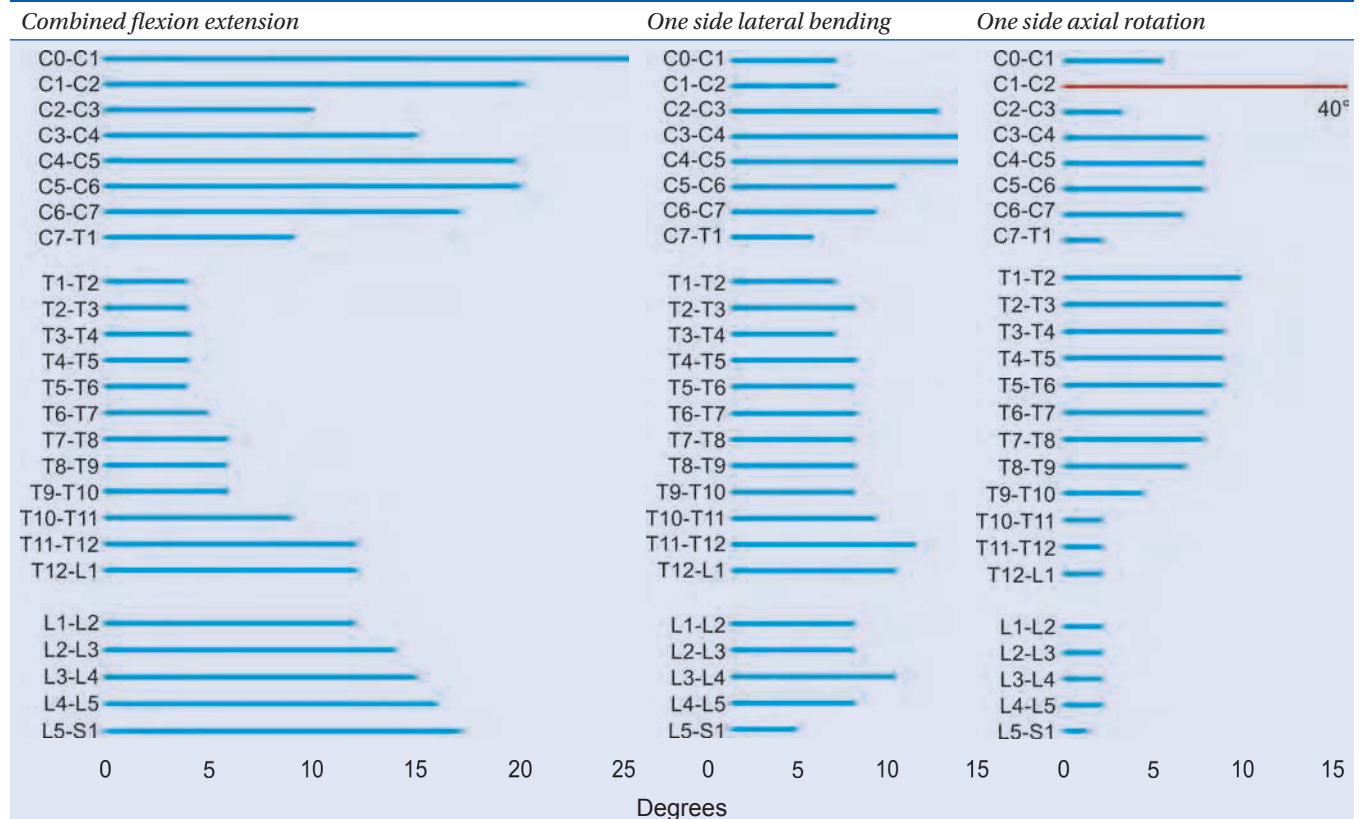
Acute trauma is caused by large forces that exceed the biomechanical limits of the spine leading to soft tissue failure. The specific pattern of injury depends heavily on the magnitude and direction of applied forces. One injury type, termed as burst fracture, is due to high intensity compressive forces on the spine. The most common compression injury involves increased pressure within the disc nucleus to the extent that the outward force on the adjacent vertebra pushes the endplate into the vertebral body. This can lead to small fractures of the trabecular bone, posterior cortical bone, and the end plate itself.¹¹ A second type of acute injury, a flexion-distraction injury, is due to a rapid forward bending movement producing a force greater than the elastic limit of the posterior ligamentous complex, leading to failure of the posterior elements.²⁰ A third acute injury, extension-distraction, is caused by hyperextension through a spinal segment. This can cause damage to the disc or vertebral body and may also damage

the posterior elements in severe cases. The final type of acute spinal injury is translational, in which shear or distractive forces lead to a highly unstable spine, and is frequently associated with injuries to the neural elements.¹¹

Cumulative Trauma

This spinal injury category is caused by repetitive forces. These repetitive forces are able to gradually damage and destroy the stabilizing structures of the spine. This long-term weakening is due to microtrauma leading to tissue injury and eventually structural compromise and failure. In contrast to acute trauma, failure from this type of trauma can potentially be avoided through lifestyle modification or alteration of training and exercise patterns. Recognition of the ongoing injury and allowing time to rest between exposures may let the body recover and can actually increase the strength of the tissue rather than leading to injury (Table. 3.2).^{8,11,21}

Table 3.2: Range of motion of different spinal segments for different types of movement including flexion/extension, lateral bending, and axial rotation.



Source: Adams M, Bogduk N, Burton K, et al. The Biomechanics of Back Pain (Second ed.). Churchill Livingstone; 2006.

Instability

Finally, instability of the spine due to repeated supra-physiologic motion causes deformation of the structures that usually limit motion. Abnormal displacement of these structures may be very small, but is often enough to stimulate pain receptors in facet joints, disc structures, and other associated soft tissue structures.^{8,11}

Mechanical Trauma

Any type of loading force can lead to tissue damage within the spine. Although disc injuries are more common than bone injuries, the bony vertebra can fail in a variety of ways. The normally strong bone is often weakened by other factors, such as malignancy, electrolyte imbalance, and decalcification, or poor nutrient supply, prior to the fracture.⁸ Vertebral fractures are typically associated with major trauma and can result in spinal cord injury and neural damage. As already mentioned, compression and burst fractures are due to high-energy axial loading, and often involve bone fragments penetrating the surrounding tissues and sometimes the spinal canal. Another injury type pertains to fractures of the posterior elements such as the pedicles and facet joints. These injuries or a combination of injury types can sometimes lead to pathology such as spondylolisthesis, or the slippage of one vertebral body on another.

A new classification and injury severity system for traumatic fractures of the thoracolumbar spine has recently been proposed based on morphologic identification of these injury patterns and associated neurologic injury as well as several clinically relevant modifiers. Studies are underway to validate this system on a worldwide basis. It is hoped that this system will provide a universally accepted method of discussing such injuries and also provide guidance to the surgeons treating them.²²

KEY POINTS

- *Functional unit of the spine:* A motion segment is the smallest physiological unit of the spine to exhibit biomechanical characteristics similar to those of the entire spine.¹² The functional spinal unit consists of two vertebral bodies separated by a cartilaginous disc, and all adjoining ligaments. This motion segment is, in itself, responsible for many of the attributes and abilities of the spine. Because the load-displacement

curve is similar, one or more functional spinal units are often used to model the spine and to measure its biomechanical properties.

- *Regional biomechanics:* Each distinct segment of the spine exhibits unique characteristics due to differences in the structures of the vertebrae, ligaments, and discs. The cervical spine is capable of the most flexibility due to combined flexion extension, axial rotation, and lateral bending. The thoracic spine demonstrates the most stability and the least mobility. Finally, the lumbar spine experiences somewhat more motion than the thoracic region yet not nearly as much as the cervical spine.
- *Spinal trauma:* Pathological loading can be divided into acute trauma, cumulative trauma, or instability categories. Examples include compression, flexion-distraction, extension-distraction, and translational mechanisms. The associated fracture patterns and treatment needs vary widely by injury type and severity.
- *Coupling motion:* Coupling is when one motion in one part of the spine induces an associated movement in a different part of the body. This is an important concept in biomechanics because it demonstrates how forces pass through the spine, and provides insight into anatomic constraints to the range of motion.

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Biomechanics of Spinal Fixation

Micah Smith, Doug Burton, Darrel S Brodke

Snapshot

- » Occipitocervical Fixation
- » Atlantoaxial Fixation
- » Subaxial Cervical Spine
- » Thoracolumbar Fixation
- » Fixation in the Osteoporotic Spine
- » Dynamic Stabilization

INTRODUCTION

Current spinal instrumentation techniques broadly range from rigid fixation, used to enhance fusion rates or treat segmental instability, to dynamic stabilization, designed to improve stability, while maintaining some mobility at the spinal motion segment. Anterior plating is the standard in the subaxial cervical and lumbar spine, while screw/rod constructs are utilized in the posterior cervical and thoracolumbar spine. Various options are available for each, and different designs or insertion techniques have different advantages. Furthermore, fusion constructs are hypothesized to affect the adjacent motion segment, leading to breakdown or degeneration. Recent basic science and clinical research studies have investigated various types of motion preservation implants that may minimize remote mechanical effects. This chapter will discuss the mechanical effects of rigid and motion-preserving implants used in the cervical, thoracic, and lumbar spine.

OCCIPITOCERVICAL FIXATION

Occipitocervical instability stems from a multitude of etiologies including trauma, neoplasm, degenerative arthritis, inflammatory disease, congenital anomalies, iatrogenic causes, and infection. Extension of instrumentation to the occiput is often needed for failure of prior instrumentation, pseudoarthrosis of atlantoaxial stabilization, or basilar

invagination after C1-2 fixation. Unfortunately, fixation from the occiput to the cervical spine usually extends to at least C2, which results in fusing the joints accountable for 50% of flexion/extension and axial rotation of the neck at the occipitoatlantal and atlantoaxial joints, respectively. Extension of the fusion below C2 into the subaxial cervical spine further reduces the range of motion, though to a lesser extent compared to the losses occurring from fusion in the upper cervical spine.¹

Fixation techniques have evolved from wire and rod constructs to occipital plates to plate and screw/rod techniques. Regardless of the technique chosen, it is imperative to have adequate stability to facilitate fusion. Early fixation techniques utilizing cerclage wires required the use of halo application postoperatively to augment the construct. With advancements in fixation, some surgeons now only utilize a hard cervical collar for a brief period after surgery.

Occipital screw placement is one aspect of construct design to consider. Options include plates designed for all midline screws versus screws placed laterally or even fixation to the occipital condyles. Midline placement of screws allows greater length screws compared to more laterally based constructs, which theoretically give strength to the construct at the sacrifice of less space for screws (Fig. 4.1).^{2,3} Medially versus laterally placed screws did not have a significant effect on stiffness of the construct in flexion/extension and rotation, but lateral bending was reduced with



Fig. 4.1: Occiput to C3 fusion completed with three midline screws and bilateral C2 pedicle and C3 lateral mass screws.

laterally placed screws.^{2,4} Recently, new techniques of fixation to the occipital condyles have been of interest if pathology around the occiput does not allow fixation to the area around the inion or if fixation there has already failed. Biomechanical analyses suggest that fixation utilizing the occipital condyle may provide sufficient strength.⁵⁻⁷

Occipital plating offers significantly more stiffness in a construct compared to the original wire and rod constructs. However, plating requires bending the plates in multiple planes for appropriate contouring and significant rod bending that may weaken the ultimate strength of the rods. Recent implant designs include precontoured rods, which are stronger than those contoured on the field. Occipital/pedicle screw and rod constructs have been found to have higher flexion/extension, lateral bending, rotational, and translational stiffness over wire constructs with or without plates.^{8,9}

Regarding cervical fixation of an occipitocervical construct, cadaveric studies investigating fixation of C1/2 transarticular screws, C1 lateral mass/C2 pedicle screws, and C2 lamina screws in occipitocervical fixation found no difference, suggesting that the technique most suitably based on the patient's anatomy and surgeon's comfort be utilized.¹⁰⁻¹² Wolfla et al. compared the presence and absence of C1 lateral mass screws in occipitocervical fixation in constructs with C2 pars screws, C1/2 transarticular screws, and C2 intralaminar screws.¹³ The addition of the C1 lateral mass screws only made a significant enhancement of fixation in the construct with C2 intralaminar screws. Additionally, the strongest construct in this study was the

use of C1/2 transarticular screws, but the authors also report that the strength of all tested constructs is likely strong enough and therefore up to the surgeon.¹³

In summary, occipital plate connected to rod/screw constructs provides the best fixation for occipitocervical fusions. Instrumentation to C1 may be omitted without significantly compromising fixation strength. Surgeons should use fixation to C1 and C2 according to their preference and the patient's anatomy.

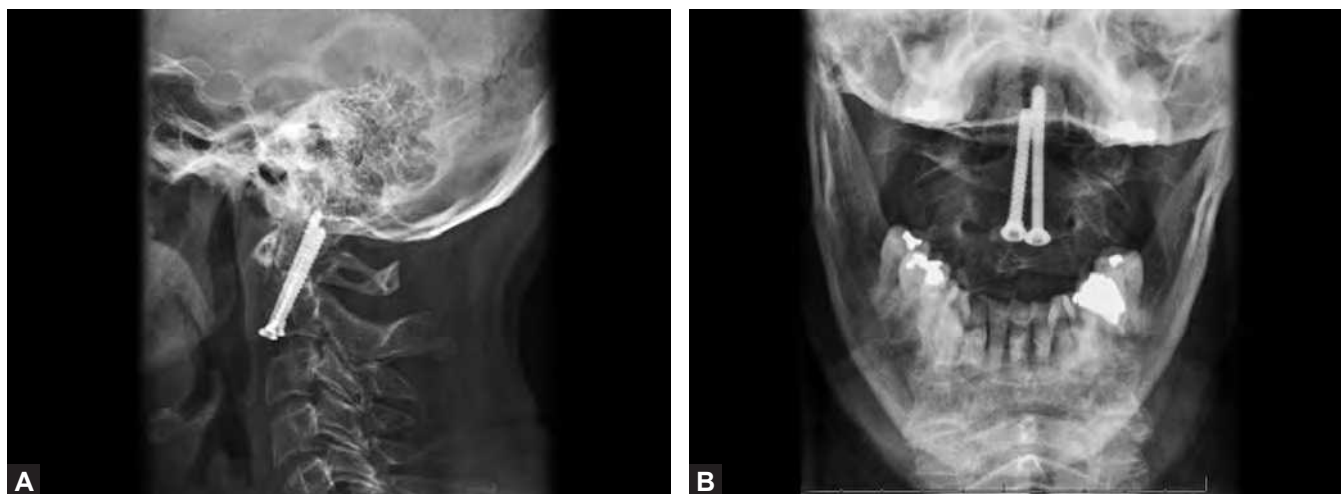
■ ATLANTOAXIAL FIXATION

Surgical stabilization can occur by anterior screw fixation of the odontoid fracture or posterior C1-2 fusion and instrumentation.

Anterior Odontoid Screw Fixation

Fixation of odontoid type II and high type III fractures is often done because of increased risk for displacement and nonunion, compared to type I fractures that are inherently stable. The two common fixation choices are ORIF and posterior spinal instrumented fusion. ORIF with screw fixation is commonly utilized for fractures, particularly in younger patients, and allows some preservation of motion of the C1/2 joint. However, the surgical technique can be challenging, and biplane fluoroscopy is required. Successful stabilization not only depends on good bone purchase, but also requires anatomic reduction and compression across the fracture. There is some controversy as to whether a single screw is adequate or a two-screw construct is needed for solid fixation (Figs. 4.2A and B). Intuitively, a two-screw construct would provide more torsional control of the fracture and improved bending stiffness. However, a cadaveric model by McBride et al. comparing two 3.5-mm cannulated screws to one 4.5-mm Herbert screw did not find that the two cannulated screws provided beneficial fixation in shear or torsional stress.¹⁴ A study by Feng et al. also did not observe any difference in shear or torsional strength between one and two double-threaded screw constructs.¹⁵ In this cadaveric study, bone mineral density did not factor into fixation strength, although ultimate failure was not tested.¹⁵ However, a retrospective review by Dailey et al. showed that 96% of two-screw constructs demonstrated radiographic stability at final follow-up compared to only 56% of single-screw constructs.¹⁶

At times, a patient's anatomy only allows for placement of a single screw. Studies, which have looked at the



Figs. 4.2A and B: (A) Anteroposterior and (B) lateral X-rays demonstrating use of a partially threaded lag screw and a second neutralization screw for osteosynthesis of a type II odontoid fracture.

strength of a single cannulated partially threaded screw compared to a variable angle headless screw, showed increased stiffness and load to failure with the variable pitch screw.¹⁷ For single screw constructs, the mode of failure is anterior screw cutout, though early reports of using a single 4.0-mm screw with smaller core diameter (2.5 mm or less) showed screw pullout or breakage as another mode of failure.^{17,18} A recent cadaveric study showed greater load to failure with the addition of a novel plate, and the mode of failure also changed to posterior displacement of the screw.¹⁹ Unfortunately, screw fixation has been found to be <50% of the strength of an intact dens.^{20,21} With that in mind, bioresorbable screws have been tested in cadavers and been found to have similar strength to that of single metal screws.^{20,21} The mode of failure was different as the bioresorbable screws themselves failed, whereas the metal screws failed by cutout from the bone.²¹ Bioresorbable screws do appear to be strong enough to hold reduction in most patients until callus is formed to stabilize the fracture before resorption begins. Other concerns with this type of fixation are the large inflammatory response elicited by the resorption of the screws and the potential osteolytic response that has been seen in other parts of the body. With the small size of the odontoid in relation to the screw, this is a legitimate concern for use at C2.

Posterior Atlantoaxial Fusion

Multiple techniques for stabilizing the C1/2 articulation have evolved, including wiring, transarticular screws,

and variations of screw/rod techniques. Screw fixation to C1 is either via a lateral mass or transarticular screw. C2 fixation options include pedicle, pars, and laminar screws. Wiring techniques, including Gallie and Brooks-Jenkins, provide significantly less stability and should be augmented with either a halo vest postoperatively or further fixation.²² While the Gallie technique places bone graft on top of the C1 posterior ring and notched over the C2 spinous process, the Brooks-Jenkins technique places two structural grafts bilaterally between the lamina of C1 and C2, with the graft placed under compression, thus increasing stability. If only unilateral fixation can be completed, the Brooks-Jenkins technique provides increased stability and is preferred.²² Pure wiring techniques offer less stiffness and allow greater range of motion, particularly in lateral bending and axial rotation compared to constructs with C1/2 transarticular screws and C1 lateral mass screws/C2 pedicle screw/rod (Harms) constructs.²³ One cadaveric study demonstrated better stability utilizing transarticular screws compared to the Harms construct.²⁴ Augmentation of the Harms construct with polyetheretherketone (PEEK) interbody spacers at C1/2 has additionally been shown to further reduce motion.²⁵ Clinically, however, fewer hardware failures were found with the Harms technique compared to transarticular screws, and a significant reduction in radiographic motion was noted at C1/2, favoring the Harms technique.²⁶ Recently, a novel device has been developed that fits into the C1/2 articulation providing interference fixation and then has a screw into the C1



Fig. 4.3: Due to anomalous vertebral artery, C1/2 arthrodesis accomplished utilizing unilateral Harms construct (C1 lateral mass/C2 pars screw) and contralateral C1/2 transarticular facet screw.

lateral mass and two lamina screws.²⁷ This technique was found to provide equivalent restriction in range of motion compared to the Harms technique.²⁷

Surgeon's experience and patient anatomy should determine the choice between transarticular screws and Harms constructs. This is especially important as aberrant anatomy of the vertebral artery has been cited to be as high as 18%.²⁸ If the vascular anatomy does not allow a normal long pedicle screw in C2, biomechanical analysis has

shown that a short pars screw offers similar immediate fixation strength.²⁴ According to some studies, C2 laminar screws are less stable than the Harms construct, but still restrict motion sufficiently to facilitate fusion.^{24,29} Other studies have shown equivalent stability of the laminar screw and pedicle screw constructs, and therefore strong consideration for their use is supported depending on the present anatomy.^{30,31} In salvage situations, mixing constructs with unilateral transarticular screw and pedicle or laminar screw construct on the other side is biomechanically equivalent (Fig. 4.3).³² Furthermore, instances where the posterior arch of C1 is absent and fusion augmentation with structural bone graft posterior is not feasible, intra-articular cages have demonstrated adequate stability.³³

In summary, decisions regarding posterior fixation constructs of the atlantoaxial joint should be made according to the patient's anatomy and the surgeon's judgment and experience. C1/2 transarticular screws and C1 lateral mass/C2 pars screw/rod construct provide adequate fixation strength; intralaminar screws are sufficient for clinical use and may be used as an alternative (Table 4.1).

SUBAXIAL CERVICAL SPINE

The subaxial cervical spine can be stabilized from an anterior approach with plate fixation, or from a posterior approach, usually using lateral mass screw-rod fixation. Alternatively, a cervical disc replacement can be performed.

Table 4.1: Comparison of biomechanical studies of C1/2 arthrodesis constructs.

Study	Type	Construct comparison	Findings
Vergara et al. ²⁶	Clinical-retrospective	C1/2 TAS to C1LM-C2PS	Less intra- and postoperative complications and less broken screws in C1LM-C2P construct. Similar fusion rate
Savage et al. ³⁰	Cadaveric biomechanical	C1LM with C2IL vs C2PS	No difference in motion after cyclic loading
Melcher et al. ²³	Cadaveric biomechanical	Gallie wiring, C1/2 TAS, C1LM-C2PS	Screw constructs significantly reduced motion compared to wiring (lateral bending, axial rotation); no difference between the two screw constructs
Papagelopoulos et al. ²²	Cadaveric biomechanical	Brooks and Gallie wiring with/without 1 or 2 TAS	Gallie wiring with 1 TAS showed most range of motion and therefore not recommended if only one screw can be placed. No difference in two-screw constructs
Sim et al. ²⁴	Cadaveric biomechanical	C1LM-C2PS (long/short), Gallie wiring, C1LM-C2IL, C1/2 TAS	TAS provided the highest stability. Use of short or long PS in C2 did not affect stability

(PS: Pedicle screw; IL: Intralaminar; TAS: Transarticular screw; LM: Lateral mass).

Anterior Cervical Fixation

Anterior cervical spine surgery is done for numerous pathologies and is one of the most frequently performed approaches for the treatment of subaxial cervical spine disorders. Restoration of lordosis, a frequent reconstructive goal, is biomechanically advantageous as a cadaveric study demonstrated increased load bearing by an anterior cervical plate when lordosis is not restored.³⁵ When faced with a patient with multilevel disease, the decision to do a two-level anterior cervical discectomy and fusion (ACDF) versus a corpectomy arises. Retrospective data evaluated sagittal alignment, cervical lordosis, graft subsidence, and the effects on adjacent levels in patients undergoing single-level corpectomy or two-level ACDF.³⁶ No difference was found between the two constructs, except that the corpectomy tended to have caudal end plate subsidence even after 6 weeks, but this did not affect overall sagittal alignment.³⁶ Hussain et al. in a finite element model showed that multilevel discectomy placed less stress on the bone-screw interface, bone graft, and end plates when compared to two-level corpectomy and was overall stronger.³⁷ However, with a greater number of fusion sites required, there remains concern for a higher rate of pseudoarthrosis.

Long anterior constructs pose different challenges. A cadaveric study showed that three-level discectomy and plate and one-level discectomy and adjacent corpectomy were stronger than a two-level corpectomy stabilized with a plate.³⁸ Setzer et al. supported this in a cadaveric study showing similar stability of a three-level discectomy with plating compared to a two-level corpectomy with plating and posterior fixation.³⁹ In fact, they showed that posterior fixation ultimately provided the best fixation and anterior plating for a two-level corpectomy did not sufficiently add stability.³⁹ However, the authors still recommend anterior plating for a two-level corpectomy to prevent graft dislodgement in the clinical setting.

Anterior cervical plating is offered in static (rigidly locked screws) and dynamic options. Dynamic options include rotationally dynamic plates where the screws are allowed to toggle in the plate and translationally dynamic plates where either the screws can translate in the plate or the plate itself translates. Dynamic plates theoretically allow controlled settling of the construct to optimize fusion incorporation, but subsidence correlates with loss of lordosis.⁴⁰ Brodke et al. simulated graft subsidence and found that the statically locked plate construct failed to

maintain load-sharing characteristics.⁴¹ They also showed that with subsidence and maintenance of the graft end plate interface, there is greater overall stiffness. Hong et al. showed increased graft subsidence and translation in the dynamic plate group, but this did not lead to a difference in fusion rates or clinical results.⁴² A randomized control trial investigated the difference between dynamic and rigid plating and found less plate complications and faster time to fusion when dynamic plates were used, but more loss of lordosis compared to rigid plating.⁴³ With the lower implant complications in the dynamic plating group, they recommend that dynamic plating be the preferred technique. Despite these findings, further investigations are warranted before this should be deemed the preferred plating design.

Screw orientation may also play a role in the biomechanics of the construct. Finite element analysis modeling demonstrates that the more divergent screws become from the plate, the more the construct transitions from a load-bearing device to a load-sharing device with increasing shear forces on the screw and increased forces on the bone graft, end plate, and bone-screw interface.⁴⁴ This remains a theoretical advantage as the neurovascular structures are at increased risk with divergent screw placement.

Stand-alone interbody cages that have screw fixation into the vertebral body are lower profile and eliminate the use of an anterior plate that may cause dysphagia, erosion into the esophagus, and other complications. However, their use has disadvantages. The fixation with screws and the structural integrity of the cage sacrifice space available for bone graft. A cadaveric study comparing a stand-alone anchored cage to locked and dynamic plates with cages found comparable stability and limitation in motion.⁴⁵ Optimization of the end plate to cage ratio is important since as this ratio decreases, the chance of graft subsidence increases as does the loss of lordosis.⁴⁶ With that said, their use in multilevel ACDF has been found to be successful clinically and to have maintained corrective lordosis.⁴⁷

Various graft options are available to the spine surgeon, including iliac crest autograft (often cited as the gold standard), corticocancellous allograft, PEEK cages, tantalum, and ceramic. A comparative study looking at iliac crest autograft alone, autograft with plate, and PEEK with plate found better maintenance of sagittal correction with plating, and no difference was seen between the PEEK and autograft plated groups.⁴⁸ This suggests that harvesting

iliac crest can be avoided without compromising sagittal alignment, and plate fixation is recommended. Initial stability is comparable among autograft, cancellous allograft, and fibular allograft.⁴⁹ Tantalum stand-alone interbody compared to autograft and plating was shown in a prospective randomized trial to have equivalent radiographic and clinical outcomes, including sagittal alignment.⁵⁰ Polyetheretherketone cages in stand-alone constructs have shown adequate fusion rates, but subsidence was seen.⁵¹ The amount of subsidence was significant compared to the immediate postoperative images, but was still acceptable according to the authors of the paper.⁵¹ Overall, bioceramics as grafts have yielded slower rates of fusion, and they must be used judiciously.^{52,53}

Posterior Cervical Fixation

Posterior subaxial cervical spine fixation is usually in the form of lateral mass screws with rods. Cervical pedicle screw placement is potentially more dangerous and certainly more difficult than lateral mass screw placement. The pedicle is bounded by nerve roots on its cephalad and caudal borders and the spinal cord medially. The vertebral artery sits in the foramen transversarium anterolaterally. A cadaveric study, where direct visualization of the pedicles was possible, still found violation of the pedicle with the screw 13% ($n = 7$) of the time.⁵⁴ In this study, the breach occurred laterally into the foramen transversarium six out of seven times, highlighting the potential complications with placement of pedicle screws in the subaxial cervical spine above C7.⁵⁴ Additionally, the morphology of the pedicles varied, requiring appropriate preoperative planning and negating a standardized approach for screw placement.⁵⁴

Biomechanically, lateral mass screws are inferior to pedicle screw placement. Pedicle screws have higher pull-out strength, lower rate of loosening, and different modes of failure compared to lateral mass screws.⁵⁵ Pedicle screws fail by fracture of the pedicle 40% of the time, suggesting that the fixation is strong enough that the bone fails before the screw-bone interface, while lateral mass screws pull out 90% of the time. Furthermore, maximum insertion torque correlated with failure of both screws, with the maximum torque of pedicle screws more than twice that of lateral mass screws.⁵⁵ The difference between the strength of lateral mass screws and pedicle screws relates to improved bone purchase with longer screws (more threads) and to purchase of stronger bone in the cortical walls of the pedicle.

Two common techniques exist for insertion of lateral mass screws: Magerl and Roy-Camille. The Roy-Camille technique utilizes a central start point in the lateral mass and aims 10° laterally and perpendicular to the posterior cortex. The Magerl technique employs a start point 1 mm cephalad and medial to the center of the quadrilateral surface of the lateral mass and aims 25° laterally and parallel to the facet joint in the sagittal plane. Barrey et al. compared the biomechanics of the two insertion techniques and found a small (~35N) but statistically higher pullout strength with the Roy-Camille technique, though this may in part be due to the testing environment.⁵⁶ Bicortical fixation was used in both techniques, and the thickness of the anterior cortex purchase was 20% higher (1.2 mm) in the Roy-Camille technique compared to the Magerl (1.0 mm). The Roy-Camille technique relies on screw purchase at the junction of the lateral mass and transverse process, whereas the Magerl technique relies on purchase in the anterosuperolateral corner of the lateral mass. Stronger purchase was also supported by the mode of failure, as the Magerl screws failed by pullout, whereas the Roy-Camille screws failed by lateral mass fracture.⁵⁶ With modern fixed-angled screw/rod constructs, unicortical screws are more commonly placed, and the longer Magerl screws may now perform better.

Cervical Disc Arthroplasty

Cervical disc arthroplasty (CDA) has developed as an alternative to fusion following anterior cervical discectomy in hopes that maintaining motion at the index level will minimize the development of symptomatic adjacent segment pathology. It has been shown that following placement of a CDA, postoperative overall cervical spine range of motion and motion at the functional spinal unit closely correlate to normal cervical motion in the lab and to preoperative motion in vivo.^{57,58} Bauman et al. in a recent biomechanical study comparing intact spines to those implanted with CDA also showed that CDA maintained motion without altering the contact pressures of the facet joints at the index level.⁵⁹ The authors noted that smaller implants were utilized to avoid “overstuffing” the disc space and to allow improved motion. This is an important technical point to consider when placing the CDA, which may otherwise lead to loss of motion and accelerated degeneration. Design characteristics also affect the loads on the uncovertebral and facet joints. Unconstrained and semiconstrained prostheses allow more load to be shared

by the native joints, increasing their stress, but Kang et al. note that this may prevent disuse osteopenia and subsequent degeneration of joint tissue.⁶⁰ Also important is the method of fixation. Implants with screw fixation may be more stable initially than keeled or toothed implants, while those with serrated edges exhibit the lowest strength for initial fixation.⁶¹

As has been stated, the often cited advantage of CDA over fusion is the preservation of normal motion and load at adjacent motion segments. Finn et al. in a cadaveric study showed that CDA was similar to the intact spine in flexion/extension and slightly less in lateral bending and axial rotation, consistent with implant design.⁵⁷ They also demonstrated increased strain at the adjacent segments in the fusion group compared to the CDA group, and it was postulated that this could contribute to degeneration and ultimately adjacent segment pathology.⁵⁷ Translational motions have also been shown to increase at levels above a fusion compared to CDA.^{62,63} This may also lead to abnormal stress on the joints and disc, accelerating degeneration.

Documentation of differences in adjacent segment pathology in the in vivo setting is less convincing to date. Kelly et al. in a prospective randomized trial with 2 years' follow-up found increased adjacent segment range of motion in the ACDF group, but not in the CDA group.⁶⁴ However, no difference was seen comparing ACDF to CDA.⁶⁴ Coric et al. in a prospective randomized trial with an average follow-up of 6 years (minimum 4 years) showed no difference in adjacent segment disease or reoperations.⁶⁵ They showed good clinical results in both groups with no difference in neck disability index (NDI) or visual analog scale (VAS) scores.⁶⁵ Garrido et al. with a 4-year follow-up comparing CDA to ACDF found more reoperations in the ACDF group for adjacent segment pathology, though not a statistically significant difference.⁶⁶ Presently, more studies with long-term data are needed to identify differences in adjacent segment pathology between ACDF and CDA.

In summary, a CDA following anterior cervical discectomy allows for more normal motion at the index level and at adjacent levels as compared to fusion. This has been shown in vitro as well as in vivo. It may decrease symptomatic adjacent segment degeneration, but this has not yet been confirmed clinically.

THORACOLUMBAR FIXATION

Most commonly, thoracolumbar fixation is achieved with pedicle screw fixation. Crossing the lumbosacral junction

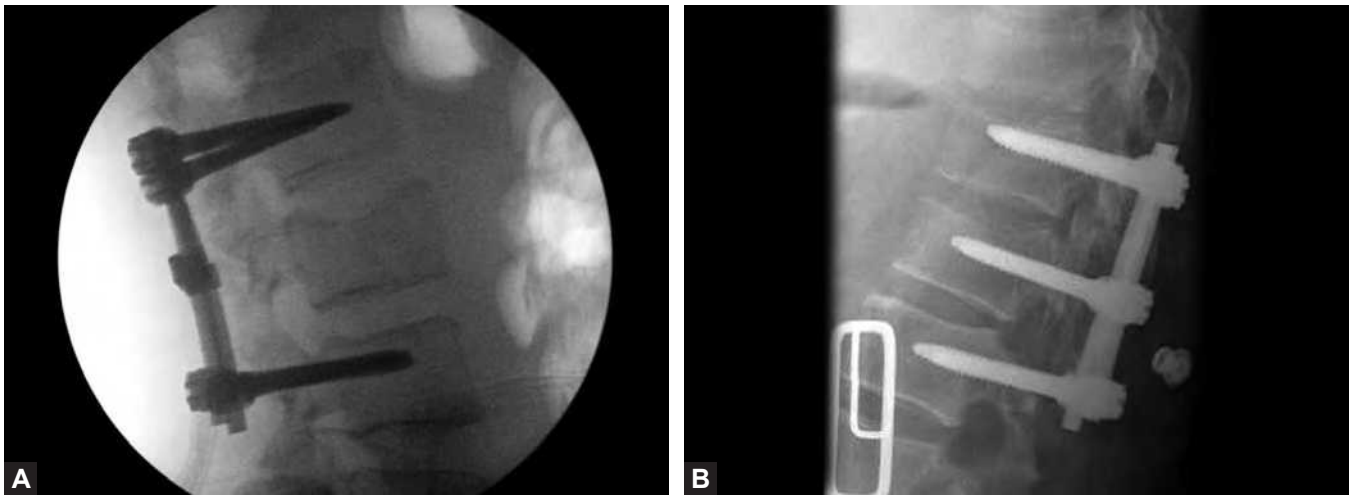
may require pelvic fixation in addition. Interbody cages may be added for further stabilization.

Pedicle Screw Fixation

Thoracolumbar fixation has evolved from Harrington rod instrumentation to Luque wire and rod or hook and rod constructs to pedicle screw and rod constructs. Pedicle screws provide rigid three-column control and fixation with higher pullout strength compared to pedicle and laminar hooks.⁶⁷ Two prominent trajectories for pedicle screw placement are the straightforward (paralleling the vertebral end plate) and the anatomic (along the true anatomic axis of the pedicle) techniques.⁶⁸ Lehman et al. found maximum insertional torque and pullout strength using the straightforward technique.⁶⁸ In salvage situations, they also found that adequate fixation is offered by the anatomic technique when the straightforward technique fails.⁶⁹ The classic "in-out-in" placement of a pedicle screw has been assessed and compared to the straightforward technique, and similar pullout strength was found in a cadaveric study.⁷⁰

Insertion technique appears important as Paik et al. found that hubbing pedicle screws, where the base of the broad tulip portion of the screw is seated firmly against the bone at insertion, actually results in lower pullout strength compared to normally inserted screws.⁷¹ Computer tomography analysis of hubbed screws demonstrated a propensity for iatrogenic fracture development and is likely the reason for decreased strength.⁷¹ While some studies suggest that pedicle screws with a tapered minor diameter can retain pullout strength after backing them out, the study by Lill et al. clearly shows a loss of stability after back out.⁷² If tapered screws are utilized, they should not be backed out to avoid loss of fixation. Various screw designs are offered for fixation. Kim et al. investigated nine different screw designs in a biomechanical analysis and found that outer cylindrical and inner conical or tapered configuration offered the highest pullout strength regardless of the bone density.⁷³

Construct strength is imperative when arthrodesis is the surgical goal. In looking at short segment fixation, Jones et al. investigated the difference between all pedicle screw constructs and screw/hook constructs (Figs. 4.4A and B).⁷⁴ They found that all pedicle screw constructs were significantly stiffer and had higher pullout strength in a cadaveric model investigating the acute strength of a construct.⁷⁴



Figs. 4.4A and B: Short-segment construct utilized for stabilization and correction of (A) burst fracture; and (B) flexion-distraction injury.

The strength and control that the construct offers are even more important when performing spinal deformity correction. Kim et al. found that pedicle screw constructs offer better correction and improved pulmonary function postoperatively compared to both hook-only constructs and hybrid constructs,^{75,76} though at an increased cost.

Overall, pedicle screw fixation provides improved spinal fixation, stiffness, and pullout strength compared to wire and hook constructs. The straightforward technique offers better biomechanical strength compared to the anatomic technique, and the spine surgeon should be cautioned regarding hubbing the screw as this weakens bone purchase.

Sacral and Pelvic Fixation

Sacral fixation is important in stabilizing the caudal portion of the construct. Lehman et al. compared bicortical S1 screws to tricortical S1 screws placed in the sacral promontory.⁷⁷ They found that placing screws into the sacral promontory significantly increased insertion torque.⁷⁷ In salvage situations, S2 alar screws can safely be placed and have yielded comparable radiographic results.⁷⁸

Fixation to the pelvis is important in deformity constructs where a long moment arm is created and control is needed to maintain the correction. Options include Galveston rods, iliac bolts and screws, and sacral alar iliac fixation (Figs. 4.5A and B).⁷⁹ Peelle et al. showed that iliac screws provided equivalent maintenance of pelvic

obliquity and scoliosis correction as Galveston rods, but with less implant complications and without the need for complex three-dimensional bending of the rods.⁸⁰ Tis et al. investigated the strength of constructs with or without fixation to the pelvis and with or without sacral screws.⁸¹ They found that including fixation to S1 provided significant improved stability as well as the addition of iliac screws.⁸¹ Lebowhl et al. found that adding iliac fixation to S1 screw fixation decreased the strain on the S1 screw in axial compression and increased the load to failure versus adding only S2 screws.⁸² Clinically, Tsuchiya et al. showed that iliac screw placement in deformity surgery or in high-grade spondylolisthesis protected S1 screws from failing.⁸³ Furthermore, they did not find any evidence of sacroiliac degeneration with at least 5 years of follow-up.⁸³ Santos et al. found that trajectory of the iliac screw to either the anterior superior iliac spine (ASIS) or the supra-acetabular location did not matter, but 9.5-mm screws had greater torque than 7.5-mm screws.⁸⁴ Screws inserted to >80 mm also had improved insertion torque.⁸⁴ Fixation down to S2 instead, utilizing iliac bolts, has been shown biomechanically to have comparable stiffness, but insertion torque is significantly less and may be the reason to prefer iliac bolt usage.⁸⁵

Recently, Chang et al. have reported on a modified technique for iliac fixation with the starting point in S2 as an alternative to the iliac starting point.^{79,86} The initial clinical reports of this technique are encouraging (Fig. 4.5B), but biomechanical testing has not been completed to date.



Figs. 4.5A and B: Fixation to the pelvis in deformity cases provides added stability compared to ending with S1 pedicle screws. (A) Iliac bolt placed with posterior superior iliac spine (PSIS) as starting point. (B) S2-ilium bolt placed with starting point just caudal to S1 neuroforamen.

In summary, sacral fixation with S1 pedicle screws into the sacral promontory is ideal, and fixation to the pelvis with iliac screws is biomechanically superior and recommended in deformity cases.

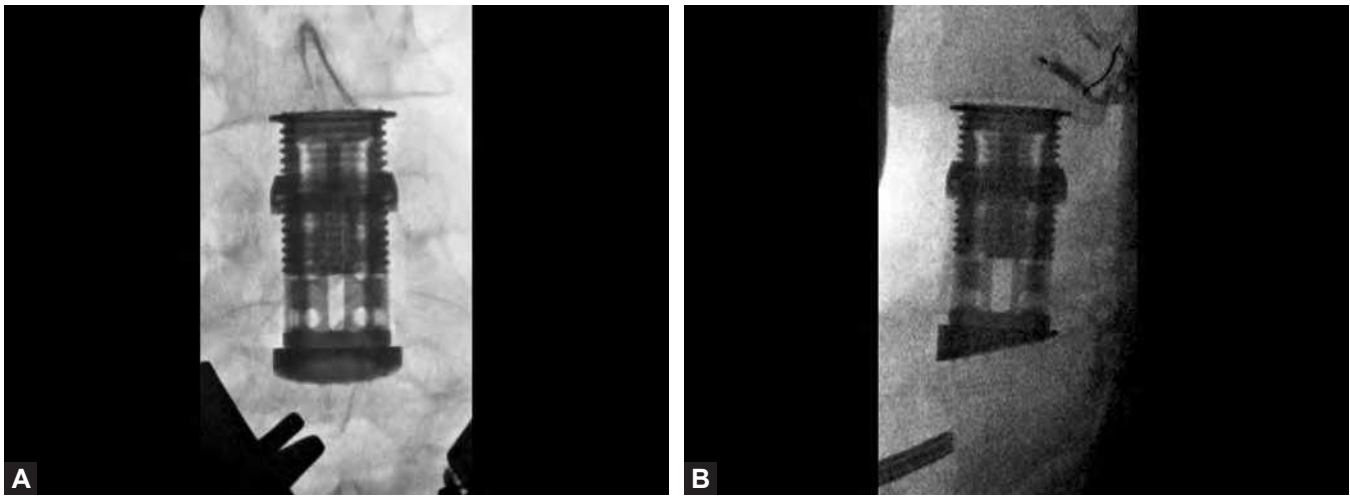
Vertebral Interbody Cages

Spine surgeons use interbody cages in the lumbar spine to increase stability and fusion rate, and sometimes to improve spinal alignment. Surgical approaches include anterior [anterior lumbar interbody fusion (ALIF)], posterior [transforaminal lumbar interbody fusion (TLIF)], posterior lumbar interbody fusion (PLIF), and lateral. From an approach standpoint, Ploumis et al. found comparable stability between TLIF and ALIF done from lateral or direct anterior approach when posterior pedicle screw fixation was used.⁸⁷ Whether an ALIF needs posterior augmentation has been addressed in a recent biomechanical study that showed anterior plating provided significant restriction to range of motion under physiologic load and improved stiffness, though pedicle screw fixation did provide further enhancement to stability.⁸⁸ It does appear that interbody cage placement is markedly benefited by supplemental fixation with anterior plate fixation or posterior pedicle screw placement.⁸⁹ When considering pedicle screw fixation, bilateral screw fixation seems to provide better restoration of segmental stability following TLIF.^{90,91}

Lateral approach interbody fusion has recently gained popularity as new techniques for neurologic monitoring

have allowed a transposas approach. Lateral interbody fusion allows for preservation of the anterior longitudinal ligament while providing access for near-complete disc removal, end plate preparation, and large interbody spacer placement.⁹² This has shown to provide significantly increased immediate stability, even as a stand-alone device. Stabilizing these constructs with bilateral pedicle screws is often recommended as well.⁹²

The use of expandable interbody cages is intriguing in tumor, infection, and traumatic reconstructions as well as in deformity (Figs. 4.6A and B). Expandable cages for PLIF with pedicle screw fixation have been shown to aid in restoring lordosis and create a stable construct.⁹³ These have also been used for TLIF (Fig. 4.7). In a corpectomy model, expandable cages did not provide adequate stability even with anterior plating, and the authors' recommendations were to avoid use as a stand-alone implant.⁹⁴ One significant concern with the use of expandable cages is the potential for subsidence with the increased end plate loading when deploying the cage and subsequent end plate fracture.⁹⁵ Clinically, this has been less of a concern, as noted in a large study on tumor reconstructions where good durability of an expandable titanium cage was noted in 95 patients, with excellent maintenance of lordosis and only minimal subsidence that did not require revision surgery.⁹⁶ Overall, expandable cages have a positive clinical history, especially when augmented with pedicle screw fixation.



Figs. 4.6A and B: Anteroposterior and lateral views of expandable vertebral reconstruction cage filled with allograft placed for infection following corpectomy. Note angled footplate to aid in restoration of lordosis.



Fig. 4.7: Expandable interbody cage placed that increases in size after implantation. It provides increased lordosis as part of sagittal balance correction.

Cross-connectors, also known as cross-links, may be a useful adjunct to the stability of a construct.⁹⁷ This is particularly important when screws are not placed at every level and in deformity cases with long constructs where axial rotation needs to be better stabilized.⁹⁸ They may also help in short-segment trauma constructs to enhance stiffness.⁹⁹

FIXATION IN THE OSTEOPOROTIC SPINE

The aging population presents a problem for the spine surgeon with the increasing rate of osteoporosis. Attempt-

ing fixation in the osteoporotic spine presents its own challenges. Numerous techniques and technologies have been employed to combat the difficulties of poor fixation. Biomechanical testing has shown that expandable screws have higher ultimate loads and energy to failure compared to standard screws.¹⁰⁰ Cement augmentation of pedicle screws using fenestrated screws has become a popular alternative. Choma et al. found that cannulated fenestrated screws with cement augmentation provided significantly more resistance to pullout compared to both solid screws with cement augmentation.¹⁰¹ The use of fenestrated screws allows for safe placement of the cement into the vertebral body and not into the canal.¹⁰¹ Pare et al. supported these findings and also found that with extraction of the screws the cement sheared off at the fenestrations, facilitating safe removal.¹⁰²

DYNAMIC STABILIZATION

Interspinous process devices/spacers have gained recent attention as less invasive methods of providing an indirect decompression for patients with lumbar spinal stenosis. Wan et al. demonstrated that an implanted interspinous device significantly increased the intervertebral foraminal area and segmental canal length at the surgical level without effects on the adjacent levels.¹⁰³ This same group also showed that an interspinous device effectively increased the interspinous process distance at the index level during several motions of the spine without increasing the interspinous process distance at the adjacent levels.¹⁰⁴

These devices are predominantly used in elderly patients, and long-term data are still needed to assess the concern for recurrent symptoms with implant displacement, subsidence, or spinous process fracture.

Lumbar disc arthroplasty remains a popular area of interest by patients and surgeons for treatment of discogenic back pain. Maintaining motion at the spinal segment after removing the disc to eliminate the potential pain generator is a biomechanically attractive option. Demetropoulos et al. demonstrated in cadaveric models that disc arthroplasty prevents the additive stress on adjacent levels occurring with fusion, while maintaining motion, though slightly less than the intact spine.¹⁰⁵ Auerback et al. additionally found that not only do forces increase at adjacent levels, but sagittal plane translation also occurs after fusion.¹⁰⁶ Gao et al. demonstrated that adjacent-level intradiscal and facet joint pressures remain near intact values, while fusion significantly increases forces on these structures.¹⁰⁷ This would presumably decrease the incidence of symptomatic adjacent segment pathology. However, the decreased load has been questioned in a study by Botolin et al.,¹⁰⁸ and clinical studies have not confirmed the change in symptomatic adjacent segment pathology. Overall, disc arthroplasty in the lumbar spine is a field that continues to advance, and more studies are needed to see long-term outcomes and effects on adjacent segments and motion preservation.

The use of dynamic pedicle screw fixation to provide stability without rigid fixation and fusion has gained some limited popularity, though it may not perform as hoped.^{109,110} Wu et al. raised the significant concern for screw loosening and found it in 20% of patients at 3-year follow-up.¹¹¹ Yu et al. have investigated combining dynamic pedicle screw fixation with TLIF in a cadaveric model to allow increased graph loading. They were able to demonstrate increased stability while facilitating loading of the graph to potentially improved fusion rates.¹¹² This requires further study with clinical assessment to support the fusion claims and clinical use.

Facet joint arthroplasty is currently being investigated as a surgical treatment for spinal restabilization after facetectomy for lumbar decompression. Phillips et al. showed that after laminectomy and complete facetectomy, facet arthroplasty restored motion at the index level as well as at adjacent levels in a cadaveric model.¹¹³ However, it remains to be seen if these systems can withstand physiologic loads over time. Sjoqvold et al. demonstrated varying moments and bone-implant loads depending on the motion intro-

duced to the spine.¹¹⁴ Rigid fixation demonstrated different loads compared to facet arthroplasty, and therefore further clinical trials are needed to determine their longevity.¹¹⁴

Dynamic stabilization constructs continue to evolve, and long-term data are needed to see if motion can be maintained without effects on adjacent motion segments.

KEY POINTS

- Occipital plate and screw/rod constructs are stronger than wire/rod constructs, and screws placed midline in the occiput are stronger than laterally placed screws. Lateral screws provide more control in lateral bending.
- When stabilizing the atlantoaxial motion segment, posterior fixation with either C1/2 transarticular screws or C1 lateral mass/C2 pedicle screw constructs is significantly stronger than wire constructs. Translaminar screws in C2 provide adequate fixation in salvage situations.
- Anterior dynamic cervical plating allows controlled settling to maintain load on the graft and facilitate faster fusion rates with fewer plate complications.
- Thoracic pedicle screw constructs are stronger than hook and wire constructs.
- Interbody cage placement provides a load-sharing environment and reduces strain on pedicle screw constructs.

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Physical and Neurologic Examination of the Spine

Charla R Fischer, Ryan T Cassilly, Melvin C Makhni, Mark Weidenbaum

Snapshot

- » General Evaluation
- » Cervical Spine Evaluation
- » Thoracic Spine Evaluation
- » Lumbar Spine Evaluation
- » Waddell's Signs

INTRODUCTION

Accurate diagnosis of spinal pathology must include a complete and thorough physical evaluation. Commonly, nerve root compression will result in radicular symptoms while spinal cord compression will result in myelopathic symptoms. The physical examination findings, including provocative maneuvers, will establish a baseline neurologic status that guides the differential diagnosis ultimately drives treatment options.

GENERAL EVALUATION

Observation

Casual observation of the patient throughout the encounter can provide valuable information. It is important to pay attention to the patient's overall behavior to observe their functional activity and to identify any signs of pain such as wincing or limping. This type of inspection is most useful when the patient is unaware that they are being observed.¹ Watch for any signs of frustration or depressed mood since these can be indicators of chronic pain or functional limitations.

More specific observation begins with assessing the patient's overall alignment, so it is important to note their posture, including any signs of torticollis, kyphosis, or

scoliosis. Ask the patient to remove all garments except underwear and to put on a gown that opens in the back to allow proper inspection of the neck, spine, pelvis, and lower extremities. Stand to the side to look for cervical and lumbar lordosis as well as for thoracic kyphosis and then move behind to view the coronal alignment of the spinal column as well as the shoulders and iliac crests.

Alignment of the head with respect to the center of the pelvis, shoulder heights, and pelvic tilt are important indicators of truncal shift.² Observe whether these findings are fixed or if they change with position. Note any other abnormalities such as prior surgical incisions, asymmetries, erythema suggesting underlying infection, muscular atrophy, abnormal pigmentation, possible indicators of neurofibromatosis such as skin tags or café-au-lait spots, or any signs of trauma (ecchymosis, lacerations, and scars). Webbing of the neck suggests underlying congenital anomaly.

While the patient walks around the room, observe their gait pattern to see if there is any impairment or rigidity and then watch them doing routine tasks such as removing their shoes to see if these can be done without difficulty. Difficulty initiating muscle activity such as that seen when rising out of a chair or starting to walk may reflect basal ganglia pathology such as Parkinson's disease. Certain gait patterns such as a spastic and scissored gait can indicate upper motor neuron pathology including potential spinal

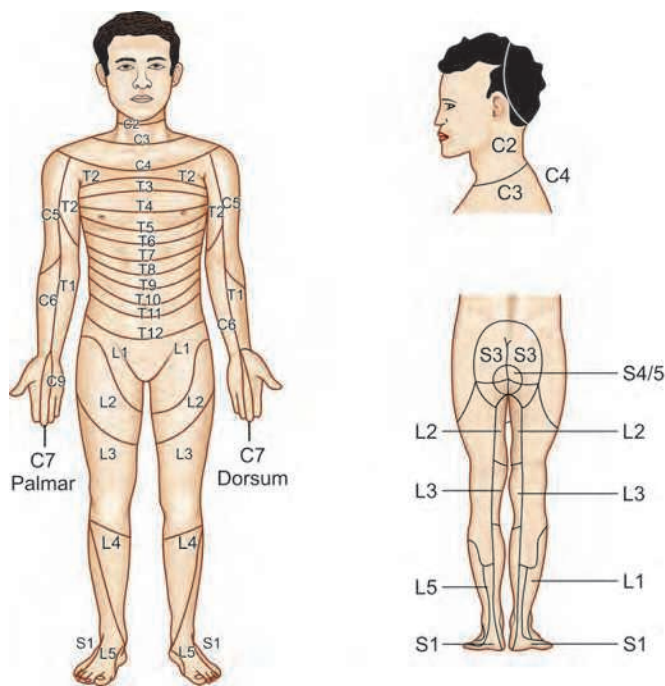


Fig. 5.1: Regional nervous sensory distribution as illustrated in a dermatome map.

cord compression, injury, or tumor. An antalgic or shortened stance phase gait indicates ipsilateral lower extremity musculoskeletal pathology. Suspicion of hip, knee, or foot pathology can be confirmed with focused examination of those areas. Tandem (heel-to-toe in a straight line) gait analysis may assist in exposing previously unseen ataxia. Observing gait abnormalities and posture may lead to a better understanding of pain patterns as well as underlying neurologic dysfunction. Such observations may also help to identify extraspinal conditions affecting gait such as intrapelvic pathology (leg length discrepancy, lower extremity contractures) as well as intrapelvic conditions, typically related to prior trauma.

Palpation

Ask the patient to stand in front of you, and palpate each spinous process with your thumb. Tenderness localized to specific spinous process could be a sign of fracture, dislocation, arthritis, or infection. Tenderness between the spinous processes suggests soft tissue injury. Any unusual prominence or recession of a spinous process should be noted, especially in the lumbar region, since these step-offs suggest spondylolisthesis.³ Palpate the facet joints in the cervical region; these are located deep to the trapezius so they may be difficult to appreciate. The nuchal ridge at

Table 5.1: Motor testing grading.

0	No muscle contraction
1	Palpable/visible muscle contraction (flicker) without motion
2	Motion perpendicular to plane of gravity (gravity eliminated)
3	Motion against gravity (can overcome gravity)
4	Motion against gravity and mild resistance
5	Motion against full resistance

the posterior occiput is often tender in paraspinal sprain and occipital neuralgia.⁴ Feel for masses and tumors in the bony and soft tissue regions that may be present as well.

Sensation

Dermatomal distribution of symptoms helps to localize the pathology to specific nerve roots or to specific peripheral nerves. Spinal nerve root dermatomes are illustrated in Figure 5.1. Sensation can be tested through the use of pinprick, light touch, light and deep pressure, vibration, temperature, and pain. Dermatomes corresponding to compressed nerve roots have significantly more sensory dysfunction than unaffected nerve roots on the contralateral side.^{5,6} However, sensory testing alone may only localize dysfunctional nerve roots half of the time.

Motor Testing Grades

Motor testing allows muscles to be graded on a scale from 0 to 5 (Table 5.1).⁷ Strength impairment on physical examination has been shown to correlate with high likelihood of associated anatomical abnormalities on magnetic resonance imaging (MRI), with a predictive odds ratio of 5.2.⁸ Specific muscular testing will be discussed in subsequent sections.

Reflexes

Before testing for deep tendon reflexes, make sure that patient is fully relaxed. Reinforcement activities can help with this since they engage other muscles while the patient relaxes the muscles of interest. For example, when testing the knee jerk reflex, ask patients having difficulty relaxing to clasp their hands together and pull apart until reflex testing is completed. Always evaluate for any asymmetry between the sides.

Reflexes are graded from absent (0) to hyperactive (4+) as seen in Table 5.2.⁷ These relative values should be

Table 5.2: Reflex response grading.

0	No response
1+	Minimal response
2+	Normal response
3+	Slightly increased response
4+	Hyperactive response, clonus

assigned keeping patient's age in perspective since "normal" reflex response may deteriorate with age. Hyperreflexia and/or clonus suggests involvement of upper motor neurons. Hyporeflexia could indicate damage to the nerve roots, peripheral nerves, neuromuscular junctions, or muscles themselves. However, hyporeflexia is more commonly the natural consequence of aging and degeneration.

Range of Motion

First attempt passive movements, and then ask the patients to perform active motions on their own. Note the differences in range of motion between passive and active motion, and verify if pain is elicited with both passive and active motion. Range of motion asymmetry due to pain rather than stiffness typically raises more suspicion of spinal pathology.

CERVICAL SPINE EVALUATION

Gait

Gait analysis can reliably indicate progression in individuals with cervical spondylotic myelopathy (CSM).⁹ Patients with a wide-based gait may have cerebellar pathology or CSM.¹⁰ Smooth, continuous gait can be disrupted with CSM because this condition may lead to spasticity with resulting loss of the hip and knee range of motion needed for a fluid gait. Gait trials can be performed in the room or with short walking tests to evaluate gait speed, stride length, and amount of time spent in stance versus swing phases.^{11,12}

Range of Motion

It is important to only examine range of motion on patients whose cervical spine has been cleared from bony or ligamentous injury. If there is a history of trauma, perform the movements carefully in order to not exacerbate any residual injury. Have the patient sit or stand upright with proper posture, shoulders relaxed, and arms by the side.

Between tests, allow the patient to recover to a neutral cervical position. As a further test, have the patient perform each range of motion maneuver again, but this time against gentle, steady resistance provided by the palm of your hand.¹³

Flexion/Extension

Stand slightly behind and at the patient's side, place one arm behind their neck, and hold their far shoulder to ensure they are only bending their neck while the thoracic and lumbar spines remain neutral. Ask them to slightly open their mouth and relax their jaw to minimize tension on the platysma.

Place two fingers on the back of the patient's head. Passive flexion is then tested by gently pushing their neck forward until tenderness or stiffness is elicited or until the chin touches the manubrium. Allow the patient to return to neutral position and then evaluate active flexion by asking them to repeat the motion without assistance to see if they can touch their chin to their chest to test the firing of the sternocleidomastoid muscle. Passive extension can be tested by placing two fingers on their forehead and slowly pushing their neck into extension, moving the head backward as far as tolerable. Active extension and function of the primary extensors (trapezius, capitis, semispinalis, and splenius) are then checked by asking the patient to repeat these motions as far as possible.¹³

Approximately 50% of cervical flexion/extension comes from the occiput–C1 junction while roughly 50% of cervical axial rotation comes from the C1–2 junction. Most patients can nearly touch their chin to their chest in flexion and it is useful to document (measuring in centimeters or in fingerbreadths) the distance of the chin from the chest in flexion and the occiput from the dorsal spine in extension.

Lateral Bending

Stand behind the patient. Place your left hand on the patient's left shoulder for stability, ensuring that the patient is not shifting their shoulders or distal spine or rotating their neck. Cup the right side of their head in your right palm and gently bend the neck toward the left shoulder. Then ask the patient to bring the left ear to the ipsilateral shoulder. Repeat the passive and active movement to the opposite side. These movements rely on action of the scalene muscles. Nearly 45° of motion in either direction is common.

Rotation

Stand behind the patient and have them face away from you. Place one hand on the patient's forehead, and cup the back of their head with your other hand. Allow your elbow to gently rest on the patient's shoulder to confirm that only the neck, not the trunk, is rotating. Next, assess the sternocleidomastoid by instructing the patients to turn their head as far as possible to each side. Many patients can rotate 75–90° in either direction. Any asymmetry should be noted. If pain is elicited with rotation, perform the rotation while the neck is in flexion to unload the facet joints. Then, repeat the motion while in extension to load the facet joints.

Palpation

Allow the patient to lie prone on the examination table, or have them sit while you stand behind them. Palpate the spinous processes of the cervical spine. The most superior palpable process is usually that of C2 and the most prominent spinous process is C7. An alternative examination method is to use your second and third digits to appreciate the spinous processes in the posterior neck while holding your thumb anteriorly on the midline with the patient supine. Note any sites of spinous process tenderness, paraspinal tenderness associated with spasm of paravertebral muscles, or any malalignment, particularly in the setting of trauma. Paracervical muscle tenderness and spasm is more common than spinous process tenderness, but it is nonspecific. Palpate the facet joints that lie deep to the trapezius muscle, so ask the patient to keep the neck muscles tension free for optimal facet examination. Also feel the trapezius muscle and the nuchal ligament, which traverses from the C7 spinous process to the inion at the base of the posterior skull. Pain at the scapular spine trapezius insertion or at the nuchal ligament may indicate possible whiplash injury from flexion and extension injury.¹³ For patients with upper cervical/occipital symptoms, palpate several centimeters lateral from the midline at the base of the occiput in the area of the greater occipital nerve.

Palpate the sternocleidomastoid muscle as it traverses from the mastoid to the clavicle. If patients are able, have them laterally extend their head against resistance while rotating their neck contralaterally. This defines the action of the sternocleidomastoid muscle. Carotid pulses can be palpated immediately lateral to first cricoid ring, but must be palpated individually to avoid simultaneous bilateral

blood flow occlusion. Next palpate the lymph nodes along the medial edge of the sternocleidomastoid muscle, which may be prominent with infection, malignancy, or other inflammatory pathology. Gently palpate the hyoid bone (near level of C3), the thyroid cartilage (near level of C4/C5), the cricoid (near C5–6), and the thyroid gland. Next, with the patient supine, examine the supraclavicular fossa as well for enlarged lymph nodes.

Sensation

Begin the sensory examination of the cervical spine by palpating the region around the thyroid cartilage, which has sensory innervations from the second cervical nerve root. The distribution of the C3 nerve root is inferior and anterior, or on the posterior-lateral aspect of the neck to the mastoid and the pinna of the ear. C4 sensory innervation extends from medial to the glenohumeral joint anteriorly to the chest as well as posteriorly to the superior scapula. C5 dermatomal extensions of the axillary nerve are more lateral and distal, including the lateral arm to the elbow. C6 innervates dorsal thumb and index finger sensation as well as to the lateral forearm that is peripherally innervated by the musculocutaneous nerve. C7 innervates the mid-dorsal forearm down to the middle finger dorsally while C8 innervates the medial forearm and T1 the medial upper arm. Pathology of C8 and T1 nerve roots can be confused with lesions of the more peripheral medial antebrachial branch of the cutaneous nerve. Sensory innervation areas are summarized in Figure 5.1 as well as Table 5.3.

Motor

The motor examination entails testing of specific muscles, deficiencies of which may correlate with various pathologies including nerve root impairment (Table 5.3). Extremities can be tested individually or simultaneously to allow for comparison between the sides.⁷

C5–C6

The deltoid and biceps are innervated primarily by C5 with assistance from C6; wrist extensors are innervated primarily by C6 with assistance from C5. To test these myotomes, begin with assessment of the deltoid muscle through shoulder abduction. Help the patient abduct the shoulder to 30° and then ask them to abduct further. Place one hand on the patient's hip to aid in trunk stabilization, and apply gentle resistance with the other hand. Next, evaluate

Table 5.3: A summary of cervical neurology.

<i>Disc</i>	<i>Root</i>	<i>Sensation</i>	<i>Muscle</i>	<i>Reflex</i>
C2-3	C3	Distal neck	Sternocleidomastoid, longus colli, rectus capitis	
C3-4	C4	Medial arm	Trapezius, splenius capitis	
C4-5	C5	Lateral arm	Deltoid, biceps	Biceps reflex
C5-6	C6	Lateral forearm	Biceps, wrist extension	Brachioradialis reflex
C6-7	C7	Middle finger	Triceps wrist flexors, finger extensors	Triceps reflex
C7-T1	C8	Medial forearm	Finger flexors hand intrinsics	
T1-T2	T1	Medial arm	Hand intrinsics	

bicep function by standing in front of the patient. Flex the patient's elbow to 90° and place one hand below the elbow and the other around the wrist to prevent forearm pronation. Ask the patient to flex in supination as you resist. Next, hold patient's forearm and ask them to extend the wrist as your other hand resists their force.

C7–C8

C7 assessment can be performed through triceps and common finger extensor testing as well as by evaluation of wrist flexion, with flexor carpi radialis and flexor carpi ulnaris receiving innervations from C7 and C8. Position as you did to evaluate wrist extension, but this time ask the patient to flex against your resistance to test the wrist flexors. Then grasp the patient's elbow with one hand and grab their ipsilateral wrist with the other. Ask them to extend their elbow and provide resistance in order to evaluate triceps strength.

C8–T1

Finger abduction and adduction, as well as finger flexion, can be performed to assess the integrity of the C8 and T1 nerve roots. Dorsal and palmar interossei are responsible for finger abduction and adduction, respectively. Ask the patient to first abduct and then adduct the fingers while you exert force in the opposing direction. You can also test the integrity of C8 and T1 through finger flexion assessment of the flexor digitorum profundus and flexor digitorum superficialis. Assess finger flexion next by having the patient clasp their fingers into a fist around your fingers and try to extend the patient's fingers if possible.

Reflexes

As previously noted, it is important for the patient to be fully relaxed during the reflex examination, so ensure that

their elbow and wrist joints are without tension. Stand in front of your patient and allow the patient's forearm to rest on your forearm of the same side. With your palm, gently hold the patient's elbow and place your thumb on the bicep tendon. With a soft, smooth motion, strike your thumb; watch for bicep contraction, and simultaneously feel for the contraction of the tendon below your thumb. If either of these occurs, the C5 reflex is intact.

The brachioradialis reflex tests the C6 nerve root. Hold the patient's forearm with your contralateral hand and ask the patient to let the wrist hang down without tension. Gently tap the brachioradialis tendon to elicit a response.

The triceps reflex assesses the C7 nerve root. Place your hand proximal to the antecubital fossa and allow the patient's elbow to hang loosely so that fingertips are pointing downward. Tap the triceps tendon with a reflex hammer proximal to the olecranon.

All three normal upper extremity reflexes are outlined in Table 5.3.

Biceps hyperreflexia has been shown to be the most sensitive for detecting myelopathy (62%), but with only 49% specificity. The triceps and brachioradialis reflexes are both more specific (78% and 89%, respectively) and less sensitive (36% and 21%, respectively).¹⁴

Provocative Testing

Cervical radiculopathy can originate from a herniated disc, foraminal stenosis, spondylosis, or any other pathology such as malignancy or infection that leads to nerve root compression. A number of provocative maneuvers are useful to assess compressive pathology.

Spurling's Test

Spurling's test, as originally described, is performed by placing axial compression on the head while rotating the



Fig. 5.2: The Spurling's test—neck extension, lateral bending, and axial loading recreates the arm pain in a patient with cervical radiculopathy due to decreased neuroforamen diameter and thus increased nerve root impingement.

neck axially and flexing it laterally to the ipsilateral side of the symptoms (Fig. 5.2).¹⁵ The test is considered positive if the radicular pain or symptoms are reproduced with the maneuver, presumably because it further decreases foraminal diameter and increases nerve root compression. Later studies have noted that adding cervical extension to the maneuver results in a higher incidence of recreating patient symptoms.¹⁶⁻¹⁸ The ranges for sensitivity and for

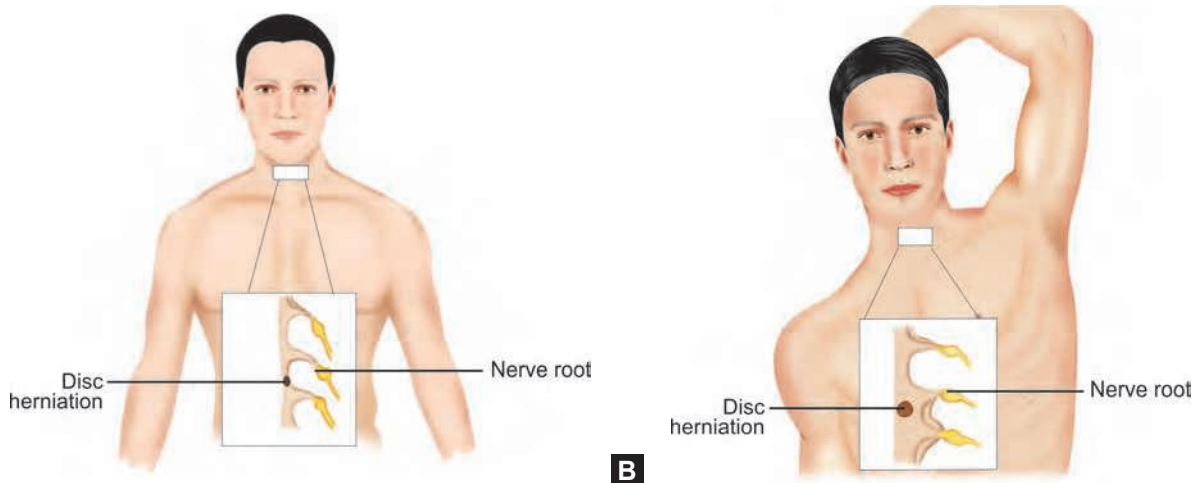
specificity using this maneuver for cervical radiculopathy are 30–90% and 92–100%, respectively.^{17,19,20}

Valsalva Maneuver

The Valsalva maneuver is performed by having the patient forcibly exhale against a closed airway. If pain or radicular symptoms are reproduced, a compressive lesion may lie within the spinal canal.²¹ This maneuver has low sensitivity (22%), but high specificity (94%).²² One study evaluating autonomic function in patients with cervical myelopathy noted a significant impairment of the autonomic response to the Valsalva maneuver when compared to controls.²³ As described later, this maneuver is also used to diagnose lumbar disc herniation.²⁴

Arm Abduction Relief Sign

Patients presenting with radicular pain sometimes find that their pain is decreased when they “hold their hand behind their neck.” This position—where the shoulder is held in abduction with elbow flexion²⁵—is believed to decrease tension on the exiting cervical nerve root, as demonstrated in Figures 5.3A and B. Abduction relieves the pressure on the exiting nerve root from herniated disc material anterior and inferior to the vertebral interspace. As the arm is adducted, the nerve root is pulled inferiorly and is increasingly compressed by the disc, reproducing



Figs. 5.3A and B: Arm abduction sign—a patient with cervical radiculopathy will place their arm on their head to decrease tension on the nerve root being compressed proximally by a disc herniation. (A) A patient with a cervical disc herniation will have increased tension on a nerve root with the arm in adduction. (B) With the arm in abduction, the nerve root is moved away from the herniated disc and thus there is less tension on the nerve root.



Fig. 5.4: Brachial compression test—compression of the brachial plexus by the physician's thumb will increase tension on the nerve root being compressed proximally by a disc herniation.

symptoms. No such relief will be found with stenosis as the nerve root impingement is fixed. The sensitivity of this arm-abduction sign was found to range from 17% to 78%,^{26,27} while specificity has been found to be 80–100%.^{19,28}

The arm-abduction sign may be used to differentiate between cervical radiculopathy caused by a herniated disc and foraminal stenosis.²⁹ It may also be used to differentiate shoulder pathology from cervical pathology. Shoulder abduction may also be used in conjunction with conservative management of cervical radiculopathy as a means to relieve symptoms.³⁰

Brachial Plexus Compression Test

Compression of the brachial plexus with the physician's thumb (Fig. 5.4) is likely to elicit localized pain in most asymptomatic individuals. However, in patients with MRI evidence of mechanical lesions of the cervical spine, this test may provoke radiating pain to the shoulder or upper extremity by increasing tension on a nerve root that is already under tension by a disc herniation. Sensitivity in this maneuver was 69%, with a high specificity of 83%.³¹

Myelopathy

Myelopathic symptoms result from upper motor neuron lesions or compression of the spinal cord, and may include gait instability, clumsiness or difficulty with upper extremity dexterity, and urinary dysfunction. Several maneuvers exist that can help assess a patient for signs



Fig. 5.5: Hoffman's sign—flicking the dorsal aspect of the middle fingernail between the examiner's thumb and index finger will cause thumb interphalangeal joint or index finger proximal interphalangeal joint or distal interphalangeal joint flexion in a patient with cord compression.

of cord compression. Pathologic findings include hyperreflexia, sustained clonus, an inverted brachioradialis reflex, or positive Babinski, Oppenheim, Hoffmann's sign, or finger escape signs. Although patients with cord signal changes on MRI are more likely to demonstrate myelopathic signs than controls, nearly 21% of myelopathic patients may not exhibit a single sign.¹⁴

Hoffmann's Sign

The Hoffmann's sign is performed by placing the patient's hand at rest and flicking the dorsal aspect of the middle fingernail between the examiner's thumb and index finger. This activates the extensor mechanism, and is considered positive if a resultant reflex contraction occurs in the thumb interphalangeal joint or index finger proximal interphalangeal joint or distal interphalangeal joint (Fig. 5.5). In a normal asymptomatic patient, no such contraction will occur. For cervical myelopathy, the Hoffmann's sign has been shown to have a sensitivity of 58–68% and a specificity of 78–84%.^{14,32,33} This finding may also be seen in asymptomatic individuals with underlying cervical cord impingement, although further imaging workup has not been shown to alter treatment plans in such patients.³⁴ A dynamic Hoffmann's sign has also been described wherein the maneuver is first performed with the head in neutral and then repeated after multiple active flexion-to-extension neck exercises. This may elicit a positive response in patients with early spondylotic myelopathy



Fig. 5.6: L'Hermite's sign—in a patient with cervical myelopathy, flexion of the neck causes increased compression of the cervical spinal cord and will create an electric shock sensation throughout the extremities.



Fig. 5.7: Finger escape sign—weakness of the intrinsic muscles leads to weaker adductors than abductors, and patients with myelopathy have difficulty with maintaining adduction of the ulnar fingers.

who may not yet have static cord compression, but whose narrowed spinal canal dynamically irritates the cord.³⁵

Inverted Radial Reflex

The inverted radial reflex (also known as inverted supinator reflex, and inverted brachioradialis reflex) is a sign of C5–C6 myelopathy and is considered positive if eliciting the brachioradialis reflex with the forearm in neutral rotation causes ipsilateral flexion of the fingers.³⁶ Sensitivity and specificity are 51%,¹⁴ and this reflex may be present in up to 25% of asymptomatic individuals.³⁶

L'Hermite's Sign

L'Hermite's sign is considered positive if flexing the cervical spine reproduces electric-like sensations into the extremities. More specifically, cervical pathology is suspected if this sign is elicited with neck flexion (Fig. 5.6) and thoracic pathology is suspected if it is elicited with trunk flexion.²¹ Low sensitivity and high specificity have been noted without exact percentages³¹ for this sign. Evidence-based evaluations of this sign for cervical pathology are lacking, but have been described for multiple sclerosis, tumors, spondylosis, and myelitis.²⁸

Fast Motor Testing

Fast motor testing may be used to assess the upper and the lower extremities for motor dysfunction due to cervical myelopathy. The *foot tapping* test may be used to analyze

the lower extremity. The patient is seated with both hips and knees at 90° of flexion, and with the heel resting on the floor the patient taps the sole of their foot as many times as possible in 10 seconds. Normal is 20 times in 10 seconds. Either test is positive if the patient cannot maintain their initial pace.

Similarly, the upper extremities can be assessed with the grip and release test. The patient fully flexes and extends their fingers as many times as possible during a 10-second interval. Normal is over 20 times in 10 seconds.

Both the foot tapping and grip and release test have been shown to have significant deficits in patients with myelopathy when compared to controls.^{37,38}

Finger Escape Sign

The patient is asked to hold their hand with all five digits adducted and extended for 30–40 seconds. The sign is positive for cervical myelopathy when the little finger is held in slight abduction at rest and cannot be actively adducted for >30 seconds, as shown in Figure 5.7.³⁸ As the myelopathy progresses, the ring finger is also weak in adduction, and in more advanced cases the interphalangeal joints become flexed and in severe cases the metacarpophalangeal joints are also fixed in flexion. The result is a patient who can only hold objects with the thumb and index finger.

Clonus

Clonus (rhythmic oscillation between flexion and extension) is typically examined at the ankle. With the patient

relaxed, the ankle is briskly dorsiflexed and maintained in a dorsiflexed position. While a few clonic beats may be normal, sustained beats (over three) are indicative of myelopathy. Sensitivity for detecting myelopathy was found to be only 13%, but with 100% specificity.¹⁴

Babinski Reflex

The Babinski or plantar response reflex is performed by stroking the lateral plantar aspect of the foot from the heel curving medially to the ball of the foot. A normal response is plantar flexion of all toes. A positive finding occurs with dorsiflexion of the big toe with fanning of the lateral toes and suggests upper motor neuron pathology.³⁹ Although it is not highly sensitive (13%), the reflex has been shown to have a specificity of 100%.¹⁴ Oppenheim's sign is closely related. This sign is positive when firm pressure applied along the crest of the tibia elicits a response similar to that seen in Babinski testing.

Additional Assessment

Care must be taken not to interpret upper extremity pain as radiculopathy when in reality it is due to primary musculoskeletal or peripheral nerve pathology. As such, a complete examination of the upper extremity should be performed as part of a comprehensive spinal evaluation.

Primary shoulder pathology may mimic cervical radiculopathy. The shoulder examination begins with general inspection. This should include evaluation of previous surgical scars, asymmetry, atrophy, arm position, and gross deformity. The muscles and bony anatomy should then be palpated with particular attention to underlying muscle tone and any tenderness. Examination of active and passive shoulder range of motion as well as rotator cuff strength is important to assess pathology such as rotator cuff tears, impingement, instability, or adhesive capsulitis.¹⁸ Patients may also present with dual disease of both the shoulder and cervical spine. Both conditions require appropriate management.⁴⁰

Radicular pain, paresthesias, and/or extremity weakness may not be due to cervical nerve root pathology and common compressive peripheral nerve pathologies such as carpal tunnel syndrome, cubital tunnel syndrome, and brachial plexopathy should remain in the differential diagnosis. Diagnosis can be made through careful history and physical examination of radial, ulnar, and median nerve function with isolated sensory examination and muscle strength testing. Specific provocative tests including

Tinel's sign at the elbow and wrist, and Phalen's maneuver at the wrist should be performed. Electrodiagnostic testing such as nerve conduction studies and electromyography can assist the physician with differentiating central versus peripheral nerve compression.⁴¹⁻⁴³

Suspicion of possible *thoracic outlet syndrome* can be assessed with the Adson test. In this maneuver, the affected arm is passively externally rotated and extended as the shoulder is abducted. The test is positive if the radial pulse is lost or if symptoms are exacerbated.

THORACIC SPINE EVALUATION

Observation

Evaluation of the thoracic spine begins with inspection of overall spine alignment in the coronal, sagittal, and axial planes. Note any deformity such as a gibbus or step-off. Check to see if the shoulders are levelled, if the pelvis is level, and if the skin folds on the trunk are levelled. Trunk balance can be estimated by hanging a weighted string from the region of C7; the weight should fall midway between the gluteal folds. Placing one hand under the patient's shoulder and another on the hip while applying gentle force may help assess curve rigidity. Have the patient bend forward letting their arms dangle in front of them above their toes to evaluate their sagittal plane. If there is a kyphosis, is it fixed or does it seem flexible? Is it a short, sharp deformity or it long and gentle? Note that forward bending may be limited by hamstring tightness such as that seen with spondylolisthesis.

Sensation

Localization of spinal cord pathology in the thoracic region relies heavily on dermatomal analysis as outlined in Figure 5.1. Reflex testing is generally of minimal use in this region since muscles innervated by thoracic nerve roots have mixed innervations. Thus, either muscle or reflex deficiencies may suggest spinal pathology, but do not help in pinpointing the specific site of the pathology.

Scoliosis Assessment

Adam's Forward Bending Test

The Adam's forward bending test is a simple maneuver to screen for thoracic or lumbar scoliosis.⁴⁴ This evaluation brings out axial spinal rotation and is performed by asking the patient to lean forward and reach with their fingers

toward their toes; a direct measurement or a scoliometer is used to measure the angle or height of prominence of one side as compared to the other. This test can also be used in the lumbar spine in cases of thoracolumbar scoliosis. Some institutions have attempted to use this test as a rapid, inexpensive screening tool for scoliosis, with sensitivity of 84% and specificity of 93% in early detection of scoliosis.⁴⁵ When forward bending consistently deviates to one side, an irritating focus in the spinal canal such as a disc herniation, a congenital anomaly, or a tumor should be suspected.

Goniometric Evaluation

Assessment of coronal plane deformity can be inferred with simple goniometric evaluation since studies of goniometric testing correlate strongly with Cobb angle measurements. Bunnell found a high correlation of 5° on scoliometer with a Cobb angle of 20°.⁴⁶ Recent studies have validated the use of goniometric evaluation of kyphosis and lordosis due to the high correlation on lateral plain films of the spine.⁴⁷

Abdominal Reflexes

Abdominal reflexes should be tested whenever there is concern for thoracic spine pathology. The patient is placed supine with their arms relaxed along the side of the body. The abdomen is stroked with a blunt instrument in each of the four quadrants around the umbilicus, starting laterally and moving diagonally toward the umbilicus. Normally, the abdominal musculature in the quadrant should contract, causing the umbilicus to deviate toward the region. Asymmetric or absent reflexes may indicate underlying cord pathology such as syringomyelia that should be further evaluated with advanced imaging.⁴⁸

Beevor's sign assesses weakness of the lower abdominal musculature, and may indicate a cord lesion at the thoracic level.^{49,50} The patient is placed supine and attempts to sit up or raise the head. A positive sign consists of the umbilicus displacing proximally as the strength of the upper rectus abdominal muscles predominate. In such situations, further workup for thoracic pathology should be pursued.

LUMBAR SPINE EVALUATION

Observation

Ask the patient to stand upright in order to determine the presence of any gross deformity. Increased or decreased

lumbar lordosis should be noted. The relationship of the pelvis to the lumbar spine should be inspected to evaluate the overall pelvic tilt.

Gait

Gait abnormalities may indicate lumbar pathology.⁵¹ With disc herniation, the patient will typically have a slow and measured gait. Decreased stride length and increased time needed from heel touch to contralateral toe lift off have been found to correlate with lumbar spinal abnormalities on gait analysis.⁵² Patients who avoid sitting and prefer to stand may have disc pathology, while those who prefer to sit or lean forward while walking are more likely to have some component of spinal stenosis. A high-steppage gait is indicative of foot drop, which may be related to nerve root compression or peripheral nerve damage.

Range of Motion

To evaluate lumbar range of motion, direct the patient to perform active movements and only perform passive range of motion testing when full active motion cannot be achieved. Ideally both evaluations can be done. Resisted movements can be performed in each direction. Pay close attention to stiffness or pain, or lack of fluidity. Newer methods attempt to measure lumbar motion exclusively without including hip motion in the measurement. Other more recent devices such as inclinometers, pelvic restraint devices, and even triaxial potentiometric systems have proven to be reliable in quantifying range of motion.^{53,54}

To assess forward flexion, ask the patient to bend forward and reach with their fingers toward their toes, and then measure the distance from the floor to the tips of their fingers. Next, test lumbar extension by asking the patient to stand upright and slowly bend backward; placing your hand midline on the lower back or allowing them to hold onto a chair helps to stabilize them. Proceed to side bending. With your hand on their posterior superior iliac spine, have the patient place their arms at their sides, and then lean first to one side and then to the other. With you and the patient in the same positions, complete the set of movements by asking the patient to rotate the trunk in both directions. When doing this, make sure the chin and shoulders remain perpendicular so that the patient is exercising the lumbar and not the cervical spine. Hip range of motion, including flexion/extension, abduction/adduction, and internal/external rotation should be assessed as well, which may reveal compounding joint pathology.

Palpation

Sit behind the patient and place your fingertips on the hips while you palpate the spinous processes with your thumbs. Palpate the iliac crests, the superior margins of which will be at the L4–L5 interspace. Also palpate the sacroiliac (SI) joint and the posterior superior iliac spine that is typically close to the S2 level. Note any tenderness, step-off, or gibbus that could suggest spondylolisthesis. In very thin patients it may be possible to palpate any lack of spinous processes, especially in the vicinity of hairy patches or areas of abnormal pigmentation, which could be suggestive of congenital anomaly. Palpate along the lateral borders of the spine to evaluate for pain emanating from the transverse processes.

Localized tenderness over the sciatic notch suggests sciatic nerve irritation, in contrast to tenderness over the axial spine or the SI joint. Tenderness over the greater trochanters is consistent with trochanteric bursitis that may mimic radicular pain. In order to rule out muscular etiologies, ask the patient to extend the neck and palpate down the paraspinal muscles adjacent to the spine. Finally, assess for pelvic obliquity and possible leg length discrepancies.

Sensation

The L1 dermatome includes the medial thigh toward the groin, the L2 dermatome is slightly more anterior and inferior, and the L3 dermatome runs medial to the patella and inferior toward the medial leg. The L4 dermatome runs down the medial leg to the medial aspect of the great toe, while the L5 dermatome includes the more lateral leg, the first dorsal webspace, and the dorsal aspect of the middle toe. The S1 dermatome most commonly includes the lateral aspect of the foot and the fifth toe. One study showed 20% sensitivity and 93% specificity of the pinprick examination for diagnosis of lumbar radiculopathy; however, these numbers increased to 36 and 92%, respectively, when the physician was made aware of the patients' MRIs prior to performing the physical examination, indicating a significant bias in diagnosis after reviewing imaging.⁵⁵

Motor

L1–L3

The L1–L3 myotomes are examined together due to their collective innervation of the iliopsoas, the primary hip

flexor. Ask the patient seated with their buttocks at the edge of their chair or examination table to lift their flexed knee upward while you resist with your hand just proximal to the knee. Compare the strength across both legs. Such lumbar spine motor examination was found to have a sensitivity between 39% and 48% and a specificity of 86% and 89%.⁵⁵

L2–L4

The quadriceps and hip adductors receive their innervations from the L2–L4 nerve roots. Evaluate quadriceps strength through knee extension while the patient remains seated. Allow the patient to sit comfortably with their knees bent while their feet are relaxed and dangling. Place one hand on the thigh and one on the anterior surface of the tibia and ask the patient to extend their leg against your resistance. Another option is to evaluate the standing patient as they rise from a *Squat*.

Hip adductors can be tested in the supine patient starting with the patient's knees extended and hips abducted so that the feet are just beyond shoulder width. Place your hands on the medial aspects of the knees and ask the patient to bring both legs together while leaving their heels on the examination table.

L4–L5

While the patient remains supine on the examination table, test hip abduction through gluteus medius strength that is controlled by the superior gluteal nerve (L5). Have the patient keep their knees extended and legs together and then have them bring their legs apart while leaving their heels on the table.

Next, ask the patient to sit for L4 and L5 testing of the tibialis anterior (TA) and the extensor hallucis longus (EHL), respectively. To test TA function, have the patient maintain their foot in dorsiflexion and inversion as you try to push their foot into plantarflexion and eversion against their resistance. After having held their foot and ankle to test the TA, move your stabilizing hand to grasp their calcaneus to test the EHL. Gently place downward pressure on the interphalangeal joint of the great toe and evaluate whether or not the patient can extend their EHL against this resistance. Another option in the ambulatory patient is to have them walk on their heels to demonstrate TA as well as EHL integrity. In some patients, weakness of the TA or EHL is only demonstrated once the muscles fatigue.

Table 5.4: A summary of lumbar neurology.

<i>Disc</i>	<i>Root</i>	<i>Sensation</i>	<i>Muscle</i>	<i>Reflex</i>
L1-2	L1	Anterior groin	Iliopsoas	
L2-3	L2	Proximal thigh	Iliopsoas, quadriceps, hip adductors,	
L3-4	L3	Distal thigh, anterior/medial knee	Iliopsoas, quadriceps, hip adductors	
L4-5	L4	Medial calf and foot	Gluteus medius, tibialis anterior	Patellar
L5-S1	L5	Lateral calf and dorsum of foot	Extensor hallucis longus, hamstrings	
S1-S2	S1	Posterior calf and lateral foot	Gastrocnemius–soleus, hamstrings	Achilles

S1

Evaluation of S1 nerve root motor function is elicited through plantarflexion or contraction of the gastrocnemius–soleus complex. With the patient seated and with their legs over the side of the examination table, ask them to plantarflex against resistance placed on the sole of the foot. Alternatively, ask the patient to walk on their toes. As noted for TA and EHL testing, in some patients, weakness of the gastrocnemius–soleus complex is only demonstrated once the muscles fatigue with repetitive muscle testing, as done through the single limb heel rise. Ask the patient to first balance themselves by holding onto a chair. Then ask them to stand on one leg and to then repeatedly rise up and down on their toes of that leg. Then repeat this on the other leg.

Reflexes

Testing for the Babinski reflex and for clonus is a standard part of the physical examination of most spine patients. In addition, reflex testing of the lower extremities should include the patellar and Achilles reflexes.

The patellar tendon reflex is indicative of L4 function. Have the patient sit beyond the edge of their examination table or chair with their legs relaxed and their knees bent, making sure that their feet hanging down but not touching the ground. Identify the superficial aspect of the infrapatellar tendon and strike it the reflex hammer.

To test the Achilles reflex (S1 function) keep the patient in the seated position and hold the foot in dorsiflexion. Palpate the Achilles tendon and strike it to elicit either a plantarflexion response or a palpable tendon contraction.

Patellar and Achilles hyperreflexia are specific for detecting myelopathy (76% and 81%, respectively), but have low sensitivities (33% and 26%, respectively).¹⁴ Table 5.4 summarizes the dermatomes, muscle groups, and reflexes for each lumbar and sacral nerve root.

Dural Tension Signs

Evaluation of lumbar spinal pathology should include provocative maneuvers. Under normal circumstances, the lumbosacral nerve roots are mobile within their foraminae and exhibit progressively increasing excursion distally.⁵⁶ However, pathologic conditions such as stenosis or intervertebral disc herniation impair this mobility and cause pain. Several useful “dural tension” signs, as described below, place tension on the nerve roots to elicit symptoms.

Straight Leg Raise

The straight leg raise (SLR) is performed by placing the patient supine on the examination table, and then raising the leg with the knee fully extended to reproduce radicular symptoms between 30° and 70° of elevation (Fig. 5.8).²¹ The sensitivities and specificities of this maneuver for lumbar disc herniation are 36–97% and 11–84%, respectively.^{57–63} Part of the inconsistency with the examination relates



Fig. 5.8: Straight leg raise—a patient with a L4-5 or L5-S1 disc herniation will feel increased tension on the affected nerve root when the leg is elevated between 30° and 70°.

to the variability in defining a positive result, such as the degree of elevation at which symptoms occur or the type of symptom produced. When comparing mid-lumbar (L2–L4) to low lumbar (L5–S1) regions, the SLR test is much more sensitive and specific for low lumbar root impingement.⁶²

Cecin's sign is a variation of this tension examination in which a Valsalva maneuver is incorporated as well. The standing patient is asked to flex the lumbar spine forward to the point where pain is experienced, and then asked to cough to simulate the Valsalva maneuver. Worsening radicular pain is considered a positive Cecin's sign, which has a sensitivity of 73% and a specificity of 95% in patients with lumbar disc herniation proven on MRI.²⁴

Lasègue's Sign, Bowstring Sign

Several other variations on the SLR test exist including the Lasègue's sign and the Bowstring sign.

Since a specific maneuver was never described by Lasègue himself,⁶⁴ the sign attributed to him has variable descriptions in the literature. One version of the positive Lasègue's sign refers to radicular pain elicited when the foot is dorsiflexed after the leg had been raised to the point of symptom reproduction and then slightly lowered. Foot dorsiflexion adds further tension to the irritated lumbosacral nerve root such that the leg symptoms are reproduced (Fig. 5.9).^{61,65} A second description involves raising the leg with knee semi-flexed and then extending the knee until symptoms are reproduced.

The Bowstring sign elicits pain during a leg raise with a semi-flexed knee followed by application of manual pressure within the popliteal fossa to tension the tibial nerve.⁶⁶ In contrast, placing tension on the medial and lateral hamstring tendons instead should not recreate pain in a patient with organic spinal pathology.⁶⁷

When correlated with intraoperative pathologic findings, the Lasègue's sign and Bowstring sign had 71% and 69% specificity for lumbar disc herniation, but did not assist with preoperatively identifying the location of the disc herniation relative to the nerve root (central, axillary, foraminal, etc.).⁶¹

Crossed Straight Leg Raise Sign, Crossed Lasègue's Sign

The crossed SLR sign, or well-leg raise sign, utilizes the fact that the SLR not only stretches the ipsilateral nerve root,



Fig. 5.9: Lasègue's sign—a patient with L4–5 or L5–S1 disc herniation will feel additional increased tension on the affected nerve root during a straight leg raise when the foot is dorsiflexed.

but also causes lateral pull on the dural sac that subsequently causes contralateral nerve root stretch.^{68,69} With this examination, an SLR is performed on the contralateral side, but symptoms are produced in the symptomatic leg. Sensitivity has been shown to be low, ranging from 4% to 42%, but with specificity higher at 85–100%.^{58–62,68,69} The crossed Lasègue's sign has been associated with accurate preoperative classification of contained versus uncontained disc herniation.⁷⁰

Femoral Nerve Stretch Test

The reverse SLR, or femoral nerve stretch test, can be used to evaluate lesions involving the more proximal L2–L4 nerve roots that innervate the femoral nerve.⁷¹ Since the more proximal nerve roots have less gliding excursion, the supine SLR is not effective in localizing them. However, the femoral nerve can be more specifically tested by placing the patient prone, passively flexing the knee, and then extending the hip. This maneuver places tension on the femoral nerve and should recreate anterior thigh pain coming from L2 to L4 nerve root irritation (Fig. 5.10). Sensitivity for detecting proximal lumbar nerve root compression is 50%, but with 100% specificity.⁶² Since this maneuver reduces tension on the sciatic nerve, pain radiating down the leg should be reduced. Hence, complaints of exacerbation of distal pain with this test may indicate a nonorganic etiology of pain.⁶⁷ Similar to the crossed SLR sign, a crossed femoral nerve stretch test may aid in the diagnosis of proximal lumbar disc herniation.⁷²



Fig. 5.10: Femoral nerve stretch test—a patient with a lumbar disc herniation at L1–L3 will feel increased tension on the affected nerve root when the hip is extended due to the increased stretch on the femoral nerve.

Sacral/Anal Evaluation

In patients with suspected spinal cord trauma, it is imperative to evaluate anal tone, saddle sensation, and sacral reflexes including the bulbocavernosus reflex and anal wink. The perianal region is innervated in a concentric circular distribution via the S3–S5 nerve roots (*see* Fig. 5.1). In the post-traumatic patient, resolution of spinal shock may be evaluated through the return of the bulbocavernosus reflex, in which reflex anal contraction is elicited with bladder trigone stimulation. This may be accomplished by squeezing the glans penis, tugging on a bladder catheter, or tapping the mons pubis. The anal wink reflex is mediated via the S2–S4 nerve roots, and causes anal contraction in response to perianal skin light touch. Patients with sacral sparing following trauma, or preservation of sacral motor or sensory function, are considered to have an incomplete spinal cord injury, which has significant prognostic value.⁷³

Sacroiliac Joint Assessments

The SI joint is a potential source of pain since it anchors the sacrum to the ilium. Since the joint itself is innervated with nociceptors from the lumbosacral nerve roots,⁷⁴ pain may also be referred to the SI from the spine. Sacroiliac pain is common, particularly after twisting or repetitive forward leaning with lifting, and must be accurately recognized. Tenderness to palpation directly over the SI must be



Fig. 5.11: Gillet test—in a patient with sacroiliac dysfunction, with hip flexion the posterior superior iliac spine does not rotate posteroinferiorly with respect to the sacrum, and the physician's thumb on the patient's posterior superior iliac spine does not rotate inferiorly.

distinguished from tenderness of the axial spine, the sciatic notch, the iliac crest, or the greater trochanter. Sacroiliitis may also be an early diagnostic feature of ankylosing spondylitis or other spondyloarthropathies.

Gillet Test

The Gillet test is used to assess the range of motion and movement of the SI joint, and it has over 85% intra- and interexaminer reliability.^{75–77} The patient stands upright with feet apart. The examiner sits behind the patient, places one thumb over the second sacral spinous process, and one thumb under the ipsilateral posterior superior iliac spine. The patient then flexes the ipsilateral knee and hip, bringing the thigh toward the abdomen (Fig. 5.11). Normally, with hip flexion the posterior superior iliac spine will rotate posteroinferiorly with respect to the sacrum, bringing the physician's posterior superior iliac spine thumb inferiorly. The absence of this movement is considered a positive test and is a sign of decreased or absent SI joint mobility.^{78,79} In asymptomatic individuals, the Gillet test was found to have a false-positive rate of 16%, with significantly higher false-positives in women (26%) compared to men (4%).⁷⁸ Sensitivity was found to be 8%, with specificity of 93% for detecting innominate torsion, but did not address assessment of SI joint hypomobility.⁸⁰ A study comparing the test to anesthetic blocks found sensitivity for detecting mobility of the SI joint to be 43%, with 68% specificity.⁸¹



Fig. 5.12: Patrick test—in a patient with sacroiliac pain, the position of flexion, abduction, and external rotation will recreate their symptoms.

Patrick Test (FABER)

The Patrick test assesses SI joint pathology. The patient is placed supine and the hip is flexed, abducted, and externally rotated (FABER) until the lateral malleolus is placed on the contralateral knee, and light pressure is placed on the ipsilateral knee to assume a more externally rotated position (Fig. 5.12). A positive result is one that reproduces SI joint pain. This test has been found to have a sensitivity of 54–77% and a specificity of 16–100% for detecting sacroiliitis.^{81–84}

Gaenslen's Test

The pelvic torsion test, or Gaenslen's test, is performed with the patient supine and the affected side of the pelvis partially off of the examination table. The contralateral hip and knee is flexed to the chest to stabilize the lumbar spine, and the examiner applies pressure to the ipsilateral hyperextended thigh (Fig. 5.13). This test is considered positive if it reproduces pain in the SI joint.⁸⁵ Sensitivity for detection of sacroiliitis in MRI-evaluated patients is low at 36–44%, but since specificity is 75–80%,⁸² the test has been shown to be reliable.⁷⁷

Yeoman's Test

The patient is placed prone, and the ipsilateral posterior superior iliac spine is stabilized while the hip is hyperextended with the knee joint flexed. This maneuver that



Fig. 5.13: Gaenslen's test—in a supine patient, the contralateral hip and knee is flexed to the chest, and the examiner applies pressure to the ipsilateral hyperextended thigh. This causes pain in a patient with sacroiliac pain.

distracts the pelvic wing and thereby placing stress within the SI joint is considered positive if SI pain is reproduced.⁸⁵ There have been no studies in the literature that assess the sensitivity or specificity of Yeoman's test.

Schober's Test

The Schober's test, or skin distraction test, is an examination of lumbar spinal mobility. As initially described, the level of the posterior superior iliac spine is marked in the midline with the patient fully erect and a second point 10 cm above is marked as well. The patient then fully flexes, and the increased distance between the points is measured. A modified Schober's test, now almost exclusively used, adds a third mark 5 cm below the posterior superior iliac spine, and measures the excursion between the superior and inferior marks.⁸⁶ In a patient with normal spinal mobility, there should be at least 5–6 cm of excursion between the points, although this has been shown to decrease with age.⁸⁷ The Schober's index has a negative correlation with the number of vertebral levels involved in ankylosing spondylitis, indicating decreased lumbar range of motion with increasing levels.⁸⁸ This test has an inter-observer reliability of 71–90%^{89,90} with high intraobserver repeatability⁹¹ and reliability of 94%.⁸⁹ It has similarly been found to be useful for differentiating axial from peripheral psoriatic arthritis with sensitivity of 51% and specificity 78%.⁹²

WADDELL'S SIGNS

The Five Signs

Successful management of the spinal disorder must address not only the organic pathoanatomy, but also the underlying nonorganic, psychosocial, and behavioral issues. Waddell developed a set of physical signs of nonorganic back pain used to further evaluate patients presenting with back pain with the goal of identifying underlying psychological and social etiologies that may compound organic pathology.⁹³ Ultimately, these signs may be used to identify patients requiring psychological evaluation rather than surgery. The five types of examination include tenderness, simulation, distraction, regional neurologic disturbance, and overreaction. A single isolated positive finding may in fact be due to an organic cause. However, when three or more of these signs are positive, a nonorganic cause of back pain is more likely.

1. Tenderness—organic causes usually relate to a skeletal structure or neuromuscular region, and typically follow a specific dermatomal distribution due to nerve root irritation. Nonorganic causes should be suspected with *superficial* tenderness, or that which exists over a *nonanatomic* region.
2. Simulation—testing that gives the appearance of a provocative maneuver but that should not actually reproduce pain from an anatomic perspective. *Axial loading* of the occiput resulting in low back pain is an example of such testing.
3. Distraction—examination while the patient is distracted can provide useful information regarding consistent or inconsistent symptoms. For example, radicular pain elicited during a supine *SLR* that disappears with a seated *SLR* may not have an anatomic basis.
4. Regional disturbances in physical findings are those that do not follow a neurologic-anatomic distribution. For example, weakness or sensory loss in a “stocking” distribution as opposed to a peripheral nerve or nerve root distribution should be evaluated for peripheral neuropathy. This can be due to a medical comorbidity (diabetic neuropathy, ischemia) or multiple nerve root involvement.
5. Overreaction to physical examination and provocative maneuvers include excessive verbalization, shaking, tremor, or facial expression.

Causes

Some studies have supported the association of Waddell's signs with underlying hypochondriasis and hysteria in men but not in women.⁹⁴ However, an evidence-based review showed that, while Waddell's signs are associated with greater pain levels, decreased functional levels, and worse outcomes for conservative and for operative treatment, they do not specifically correlate with psychological distress, secondary gain, and nonorganic pathology.⁹⁵ Care must be taken before any conclusions can be drawn when these signs are elicited, and their presence should not preclude complete examination of the patient.

KEY POINTS

- A thorough physical examination of the spine is paramount to appropriate care of the spine patient. In many cases, the diagnosis can be made before the examination is complete, but every step of the evaluation should be made to avoid missing any key areas of the patient's disease process.
- A vast amount of information can be obtained through careful observation of a patient prior to beginning the examination. Many patients are not aware that you are examining how they walk or move before or after the evaluation and this can help you understand where their pain is.
- In general, cervical or lumbar disc herniation leads to specific nerve root involvement and will likely lead to pain or paresthesias in one dermatome, with weakness in one muscle group, and one blunted reflex. In contrast, cervical or lumbar spinal stenosis will lead to paresthesias in multiple dermatomes, weakness in multiple muscle groups, multiple areas of hyperreflexia (cervical), or multiple blunted (lumbar) reflexes.
- Specific provocative tests on physical examination provide a higher sensitivity and specificity than the routine examination. Patients with positive localizing tests are more likely to have imaging indicative of spinal pathology.
- Waddell's signs for nonorganic back pain are helpful to determine if a patient's pain is unlikely to be originating from organic spinal pathology. The presence of these signs does not necessarily mean that the patient is malingering but do suggest that their pain may be due to factors unrelated to the spine.

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Electrodiagnostic Studies of the Spine

Toshihiko Taguchi, Yasuaki Imajo, Mark L Dumonski

Snapshot

- » Factors Influencing Electrodiagnostic Studies
- » Needle EMG
- » H Reflex
- » F-Wave
- » Motor-Evoked Potentials
- » Central Motor Conduction Time
- » Clinical Application of CMCT
- » Cauda Equina Conduction Time
- » Spinal Cord-Evoked Potentials
- » Case

INTRODUCTION

Electrodiagnostic examination is composed of two distinct but complementary techniques: nerve conduction studies (NCS) and needle electromyography (EMG).

During NCS, the electrical responses evoked by nerve stimulation in muscle and nerve are recorded and analyzed. Both motor and sensory NCS are performed. Whenever motor NCS are performed, recording electrodes are placed over a muscle and its tendon.

For all routine motor NCS, a small muscle of the hand or foot serves as the recorded muscle, and the nerve supplying it is stimulated at two points along its course: the elbow and wrist in the upper extremity, and the knee and ankle in the lower extremity.

Nerve conduction studies can be used to (1) diagnose diffuse polyneuropathy, (2) pinpoint a focal nerve lesion, and (3) evaluate the severity of a known nerve injury.^{1,2} Polyneuropathy is diagnosed electrophysiologically by abnormalities in multiple nerves. The pattern is usually diffuse and symmetrical. Focal lesions (entrapments) are primarily myelin abnormalities caused by ischemia, or by myelin sheath distortion or slippage. Examinations of a short segment are optimal. The distal segment may conduct normally or abnormally, depending on the severity of the lesion. Proximal nerve lesions and the brachial

plexus lesions are difficult to document using routine distal conduction examinations. H reflexes and F-waves may be helpful in these conditions (these are discussed later in the chapter).^{3,4} If a response can be evoked across the site of an injury, this rules out a complete lesion. If adequate time has elapsed for severed fibers to undergo Wallerian degeneration (3 or 4 days), an intact response distal to the injury suggests something other than a complete lesion.⁵

For sensory NCS, either a sensory nerve or a mixed nerve (motor and sensory nerve) is stimulated at one point. Sensory nerve action potentials (SNAPs) are recorded at a set distance along the nerve fibers. The cell bodies for the motor axons are situated within the anterior horns in the spinal cord. On the other hand, the cell bodies for the sensory axons are located within the dorsal root ganglion (DRG). Lesions within the spinal canal (myelopathy and radiculopathy) involve sensory fibers that are proximal to their cell bodies in the DRG, rather than distal to them. These lesions do not affect the SNAP amplitude because the injured sensory fibers degenerate centrally from the lesion site rather than peripherally, thus leaving the peripheral sensory fibers intact. By contrast, lesions involving the plexuses and peripheral nerves cause sensory fibers to degenerate distally from that point, resulting in low-amplitude SNAPs or a failure to elicit SNAPs.

FACTORS INFLUENCING ELECTRODIAGNOSTIC STUDIES

Age

Conduction velocity in newborns is approximately half of adult values; velocity increases until normal adult values are attained by 3–5 years of age. In adults, the conduction values vary slightly from decade to decade, but this is usually of little significance until over age 60 years. Older subjects usually have slower conduction and lower-amplitude responses, and this slower conduction is especially evident in sensory studies.

Temperature

Many studies have demonstrated the effect of temperature on human conduction velocity.^{6–8} Velocity is proportionally related to temperature at a rate of 0.7–2.4 m/s for each degree centigrade. This effect decreases at higher temperatures, becoming less significant above approximately 30°C skin temperature. The shape of the response is also affected. Latency, duration, and amplitude—all increase as temperature falls.⁹

Gender

The difference between male and female subjects was found to be significant in a few studies. This included sensory studies of median, ulnar, radial, sural, and superficial peroneal nerves^{10,11} and in motor studies of the ulnar nerve.¹² Generally, females are found to have higher amplitudes, but this may be due to females generally having smaller extremities resulting in female nerves being closer to the recording electrodes.

NEEDLE EMG

Unlike NCS, needle EMG only assesses the motor fibers. During needle EMG, a recording needle electrode is inserted into various muscles and the electrical activity generated within them, either spontaneous or voluntary, is evaluated visually and aurally.

The assessment of needle EMGs is divided into three phases: (1) the insertion phase, (2) the “at rest” phase, and (3) the activation phase. During the insertion phase, the electrical activity resulting from needle movement in a relaxed muscle is studied. In normal muscles, each insertion injures several individual muscle fibers, thus generating

a small burst of electrical potentials referred to as insertional activity. During the “at rest” phase, there is normally electrical silence. However, various types of spontaneous activity (fibrillation potential and positive sharp potential) occur with many disorders of the neuromuscular system. Fibrillation potentials are spontaneous and usually fire regular action potentials in individual muscle fibers. Fibrillation potentials and positive sharp potentials can be observed in both myopathic and neuropathic processes. Fasciculation potentials are spontaneous action potentials and are indicative of motor unit irritation rather than denervation. During the motor unit potential (MUP) activation phase, the muscle being assessed is contracted by the patient at the examiner’s request, thereby causing voluntary MUPs. Motor unit potentials are evaluated in terms of their firing characteristics and their configurations.

Many electromyographers are able to diagnose radiculopathy and entrapment neuropathy with needle EMG abnormalities in a myotomal distribution.¹³

Involvement of the reflex arcs, anterior horn, lateral corticospinal tracts, nerve roots, and cauda equina is often assessed by electrophysiological examination. The relevant electrodiagnostic parameters include the H reflex, F-wave, central motor conduction time (CMCT), and cauda equina conduction time (CECT). In conditions involving cervical myelopathy, it is difficult to accurately diagnose the specific level of the lesion. However, evoked spinal cord potentials using peripheral nerves, transcranial stimulation, and spinal cord stimulation have been used at an attempt to diagnose the specific level of the lesion.^{14,15}

H REFLEX

The H reflex is a monosynaptic segmental reflex named after Dr Johann Hoffmann, a German neurologist who described it in 1918.¹⁶ Although it is present in many nerves in newborns, the response disappears by adulthood. In the adult the H reflex is usually studied in the tibial nerve, although it has also been studied in the flexor carpi radialis muscles. It is analogous to the ankle tendon reflex. There is a single synapse in the spinal cord, which results in an efferent discharge of the S1 (and possibly L5) anterior horn cells, whose fibers travel through the sciatic nerve to the gastrocnemius, soleus, and other tibial nerve-innervated muscles. The H reflex can only be obtained consistently in adults by stimulating the tibial nerve in the popliteal fossa. It is evoked at low stimulus intensity and its maximal amplitude exceeds that of the direct muscular response compound muscle action potentials (CMAPs). At higher

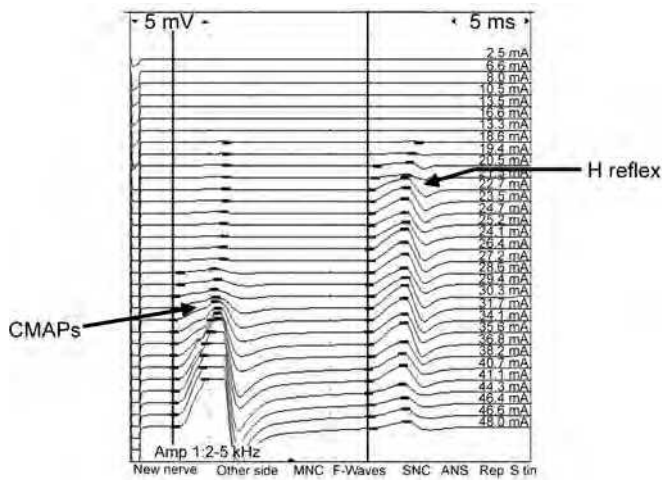


Fig. 6.1: H reflex. Demonstration of increasing stimulus strength during progression from the lowest to highest sweep. Note the appearance of the H reflex at low-stimulus intensity and its subsequent inverse relationship with compound muscle action potentials with increasing stimulus intensity.

stimulus intensities, the amplitude decreases and varies inversely with the CMAP amplitude. The H reflex should be absent at supramaximal stimulation. When elicited, the response remains constant if the stimulus is maintained constant (Fig. 6.1).

By contrast, the F-wave is best evoked with supramaximal stimulation and its amplitude is only a fraction of the CMAPs. Moreover, it is not constant and varies in amplitude and latency, even with constant stimulus.

Typically, the sacral plexus, sciatic nerve, and tibial nerve are all evaluated by the H reflex.

F-WAVE

The F-wave was first described by Magladery and McDougall in 1950¹⁷ and represents long-latency responses present in many nerves in the adult. Unlike the H reflex, F-waves have no sensory component and are not the result of a reflex arc. Instead, they are thought to represent anterior horn cell depolarization caused by antidromic stimulation of motor fibers. F-waves must be distinguished from H reflexes. F-waves are best evoked by supramaximal stimulation, and the responses are small compared with the direct muscular response (CMAPs). F-waves are not constant, they vary in latency and amplitude, and they are not always present with each stimulus (Figs. 6.2A and B). F-waves provide an opportunity to measure conduction along the most proximal segment of a nerve, including the root.

This makes it useful for pathology involving the nerve root or proximal nerve pathology.

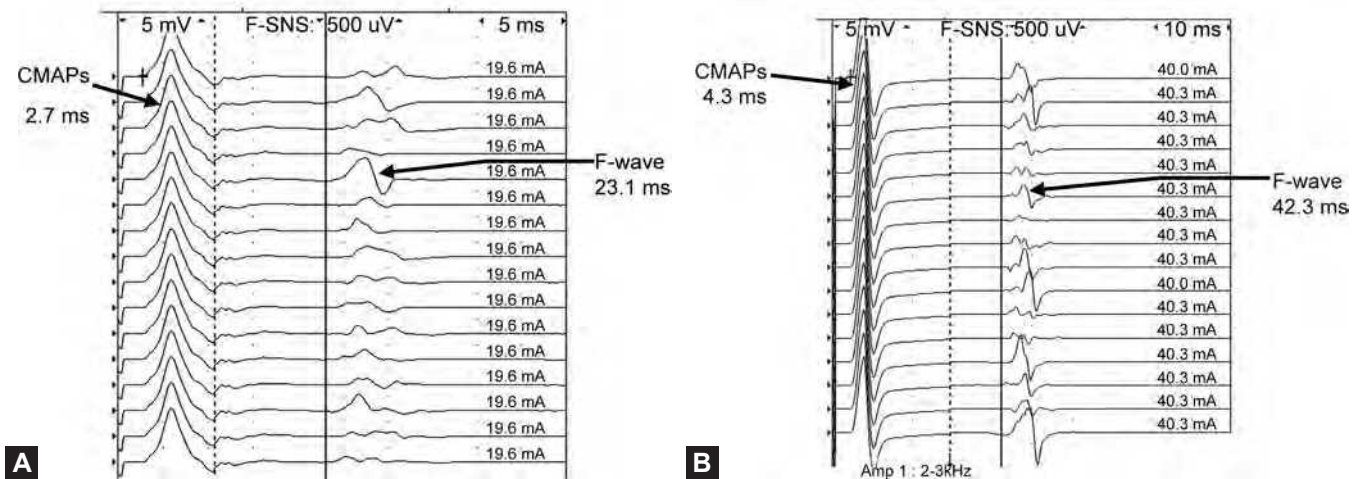
MOTOR-EVOKED POTENTIALS

Beginning in 1980, techniques were developed to stimulate the motor cortex using surface stimulation. Merton and Morton utilized brief, high-voltage stimuli.¹⁸ Subsequently, Barker et al. developed magnetic stimulation.^{19,20} These methods have been used to stimulate cortical structures as well as the spinal cord and root regions. The safety, side effects, reliability, and clinical utility of these procedures are still being evaluated. They provide an assessment of descending motor pathways from the cortex, through the spinal cord and to the periphery. High-voltage methodology requires an output of 750 V and low-output impedance. Magnetic stimulation is via a flat helical coil. The high-voltage technique provides optimal stimulus localization. However, it is difficult to precisely localize the point of stimulation with the magnetic stimulation procedure. The advantages of the magnetic stimulation procedure are that it is painless and can be delivered without skin contact.

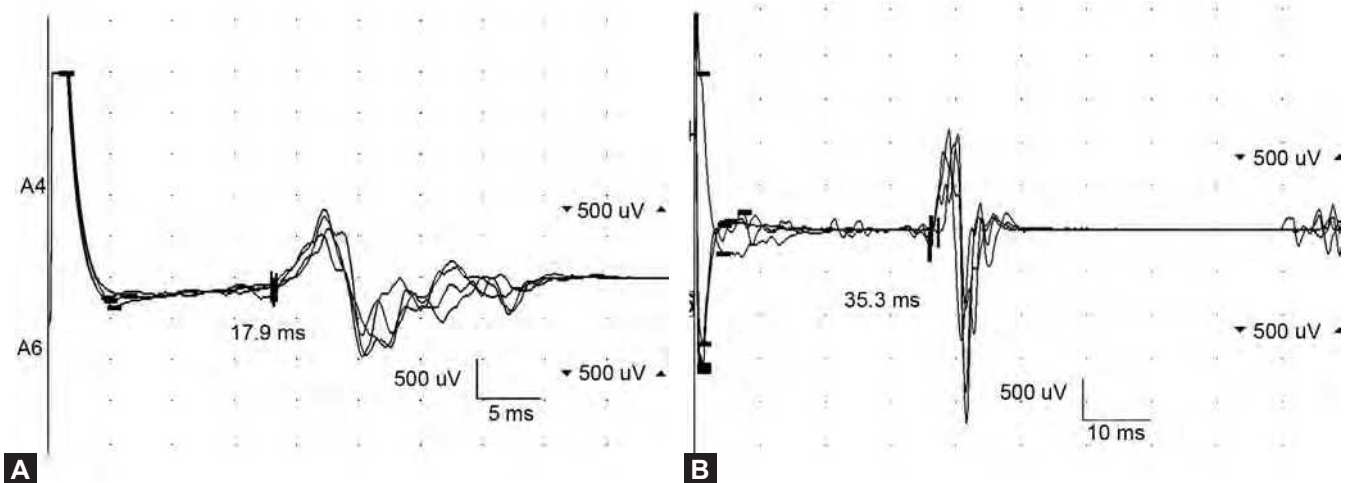
CENTRAL MOTOR CONDUCTION TIME

Transcranial magnetic stimulation allows noninvasive investigation and objective assessment of the efferent nerve functions through the corticospinal tract.²¹ Abnormal CMCT after magnetic stimulation was reported in up to 84% of patients with cervical myelopathy.²²⁻²⁴ It is common practice to calculate the CMCT of the proximal limb muscle by subtracting the motor-evoked potential (MEP) latency of the magnetic neck stimulation from the magnetic cortical stimulation.²⁵

Cervical root impulses in the foraminal region have been elicited by magnetic neck stimulation.²⁶ When this method of investigation is used in the CMCT, false-positive results can occur in patients with concomitant intraforaminal cervical root lesions. Thus, Ofuji et al. reported an alternative technique to calculate the CMCT using tendon reflex latency (T-response).²⁷ Central motor conduction time is measured by subtracting the peripheral conduction time, which is calculated using the T-response for the biceps brachii muscle. For the distal limb muscles, the CMCT is calculated by the F-wave (Figs. 6.3A and B). However, recording the F-wave from the proximal upper limb muscles is technically demanding.



Figs. 6.2A and B: F-wave. (A) Ulnar nerve stimulation at the wrist with surface recording from the abductor digiti minimi (ADM). Compound muscle action potentials (CMAPs): direct response, the F-wave is variable, changing from response to response. CMAP latency is 2.7 ms. The shortest F-wave latency is 23.1 ms. Peripheral conduction time (PCT) is calculated from the CMAPs and F-wave after supramaximal electrical stimulation of the ulnar nerve at the wrist for ADM. The PCT is 12.4 ms, calculated as $(2.7 + 23.1 - 1)/2$. (B) Tibial nerve stimulation at the ankle with surface recording from the abductor hallucis (AH). Compound muscle action potentials: direct response, the F-wave is variable, changing from response to response. CMAP latency is 4.3 ms. The shortest F-wave latency is 42.3 ms. PCT is calculated from the CMAPs and F-wave after supramaximal electrical stimulation of the tibial nerve at the ankle for AH. PCT is 22.8 ms, calculated as $(4.3 + 42.3 - 1)/2$.



Figs. 6.3A and B: (A) MEPs elicited in the ADM of a normal volunteer by magnetic stimulation of motor cortex CMCT in the upper extremities (ADM) is 5.5 ms: 17.9-12.4 (B) MEPs elicited in the AH of a normal volunteer by magnetic stimulation of motor cortex CMCT in the lower extremities (AH) is 12.5 ms: 35.3-22.8.

CLINICAL APPLICATION OF CMCT

Central motor conduction time can be used to electrophysiologically evaluate the corticospinal tract. Abductor digiti minimi (ADM) muscles are mainly innervated from C8 and T1 segments, whereas abductor hallucis (AH) muscles are mainly innervated from S2 and S3 segments.

Therefore, corticospinal tract conduction block at the level of or rostral to the C7 segment results in the prolongation of CMCT in upper extremities (ADM). Corticospinal tract conduction block at the level of or caudal to the T2 segment results in the prolongation of CMCT in lower extremities (AH) and a normal CMCT in upper extremities (ADM). Kaneko et al.²⁸ proposed a mechanism for prolonged

Table 6.1: Normal value of CMCT.

CMCT (ms)	Kaneko et al.	Nakanishi et al.
ADM	4.2±1.1	7.2±1.4
AH	11.1±1.5	14.2±2.0

(ADM: Abductor digiti minimi; AH: Abductor hallucis).

CMCT in compressive cervical myelopathy that involves a minor slowing of conduction in the corticospinal tract after transcranial electric stimulation. The slowing of spinal motor neuron firing of multiple corticospinal descending volleys could explain the prolonged CMCT without pronounced slowing of corticospinal conduction in compressive cervical myelopathy. Table 6.1 shows normal values for CMCT in the upper and lower extremities.^{28,29}

Nakanishi et al.²⁹ measured CMCT in the upper extremities (ADM) and CMCT in lower extremities (AH) in 20 patients with compressive thoracic myelopathy (CTM), 92 patients with compressive cervical myelopathy (CCM), and 18 control subjects. Central motor conduction time in the lower extremities (AH) of patients with CTM were significantly longer than in control subjects, although no significant differences were observed for upper extremities (ADM). Both the CMCT in upper (ADM) and lower extremities (AH) of patients with CCM were significantly longer than those of controls. The ratio of CMCT in upper extremities (ADM)/CMCT in lower extremities (AH) in the CTM group was significantly lower than in the other groups.

In contrast to the above study, Taniguchi et al. evaluated patients with CTM by recording MEPs from the erector spinae muscles at 12 serial vertebral levels and compared the results with data from normal subjects.^{30,31} The examiners were able to identify all cases of CTM at lesions rostral to the T10–11 level, and were not able to identify lesions at or caudal to T10–11.

CAUDA EQUINA CONDUCTION TIME

Lumbar spinal stenosis (LSS) is a degenerative disease of the spine, and magnetic resonance imaging (MRI) is the method of choice for evaluating this condition. However, asymptomatic LSS is not an uncommon finding in the healthy population.³² In addition, the severity of MRI findings does not always correlate with symptoms associated with LSS.³³ Electrodagnosis is an important testing modality in the investigation of LSS, and numerous studies have suggested that a slowing or blocking of root nerve conduction is associated with neurogenic claudication^{34–42} (Fig. 6.4).⁴³

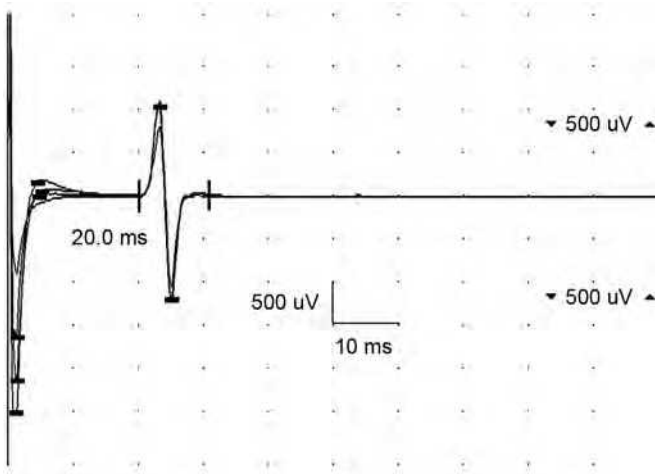


Fig. 6.4: Cauda equina conduction time using F-waves was calculated by subtracting the peripheral conduction time (PCT) from the onset latency of the motor-evoked potentials (MEPs) after the first sacral magnetic stimulation. The onset latency of MEPs after the first sacral magnetic stimulation is 20.0 ms. Cauda equina conduction time is 2.8 ms: 22.8–20.0.

SPINAL CORD-EVOKED POTENTIALS
PN-SCEPs: Peripheral Nerve Stimulation

Gasser and Graham recorded potentials from the dorsum of the spinal cord of cats evoked by stimulation of a dorsal root.⁴⁴ Subsequently, many investigators have analyzed spinal potentials evoked by stimulation of both the dorsal root and peripheral nerves.^{45,46} Shimoji et al. reported a safe and simple method of recording spinal cord-evoked potentials (SCEPs), both for the clinical use in the diagnosis of spinal diseases and for basic research on the origin of SCEPs.⁴⁷ However, the action potentials that result from peripheral nerve stimulation are usually too small to allow extradural observation. Thus, attempts have been made to record spinal-evoked potentials of high amplitude. High-amplitude SCEPs are most accurately and safely recorded when the stimulating electrode is inserted into the epidural space.

MN-SCEPs: Spinal Cord-Evoked Potentials after Median Nerve Stimulation

MN-SCEPs are recorded intraoperatively, with the median nerves being stimulated at the wrist (Fig. 6.5). The stimulus intensity is set at 1.5 times that required to produce a thumb twitch in an awake patient.

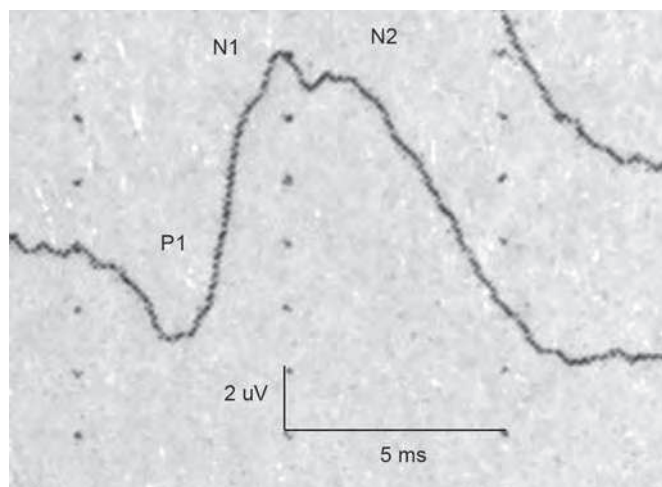


Fig. 6.5: MN-SCEPs. Normal MN-SCEPs consist of the spike (P1N1) and subsequent slow negative deflection (N2) in the posterior recording.

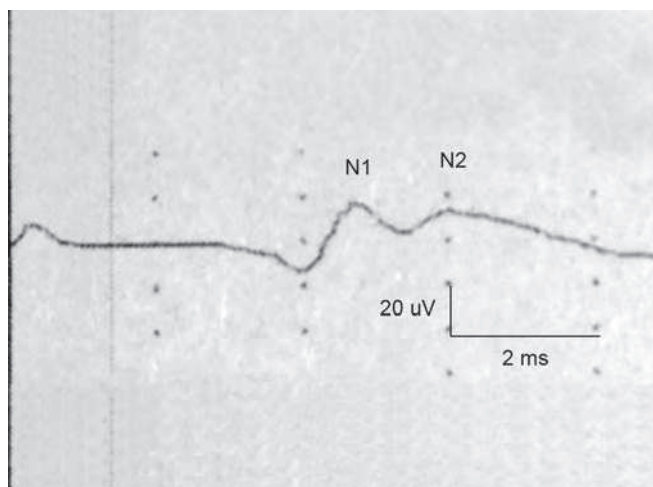


Fig. 6.6: SC-SCEPs. Normal SC-SCEPs consist of two negative deflections (N1, N2) in the posterior recording.

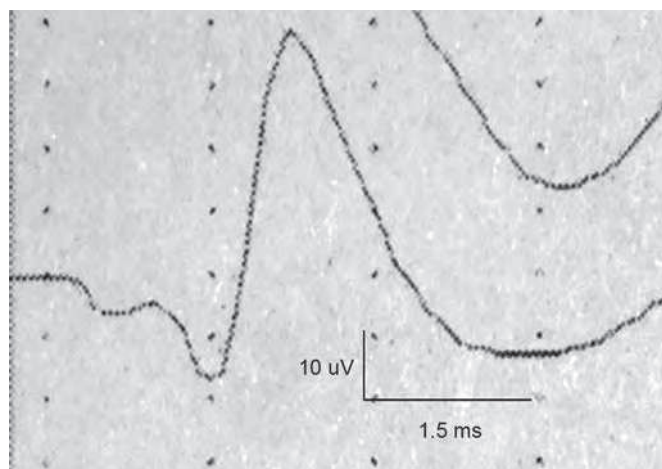


Fig. 6.7: TES-SCEPs. Normal TES-SCEPs consist of one negative deflection in the posterior recording.

SC-SCEPs: Spinal Cord Stimulation

Since the time Bremer reported the first spinal electrogram, the importance of its origin in various animals has been debated.⁴⁸ Brust-Carmona et al. examined in detail the origin of each component of spontaneous spinal electrograms in cats.⁴⁹ The recording of spinal electrograms with surface leads from the skin is not possible in humans because of the small amplitude of the spinal electrogram and interference from other sources.

Magladery et al. obtained action potentials from the dorsum of the spinal cord with electrodes introduced intrathecally into the subarachnoid space of human

volunteers.⁵⁰ However, this method involves many risks and is not amenable to routine clinical utilization.⁵⁰ Shtark recorded spontaneous spinal electrograms in humans using electrodes introduced into the epidural space; however, details of the electrode placement were not described in this report.⁵¹

SC-SCEPs represent an aggregate of conducted potentials that originate in both sensory and motor fibers of the white matter of the spinal cord (Fig. 6.6). Consequently, the amplitude and conduction velocity of the conducted SCEPs is likely to decrease in proportion to the number of injured nerve fibers.⁴⁹

TES-SCEPs: Transcranial Electric Stimulation

Levy recorded SCEPs from the human spinal cord evoked by transcranial stimulation or direct stimulation of the cortex (Fig. 6.7).⁵² These stimulation methods primarily activate the pyramidal system in the anterior spinal artery territory of the spinal cord.^{53,54} A common use for this technique is intraoperative monitoring of the spinal cord during procedures that may result in spinal cord injury. For procedures such as these, PN-SCEPs and SC-SCEPs have been shown to be incomplete indicators.

CASE

A 62-year-old man with a 24-month history of progressive numbness and clumsiness of both hands and with a gait disturbance was evaluated in our hospital. He had no

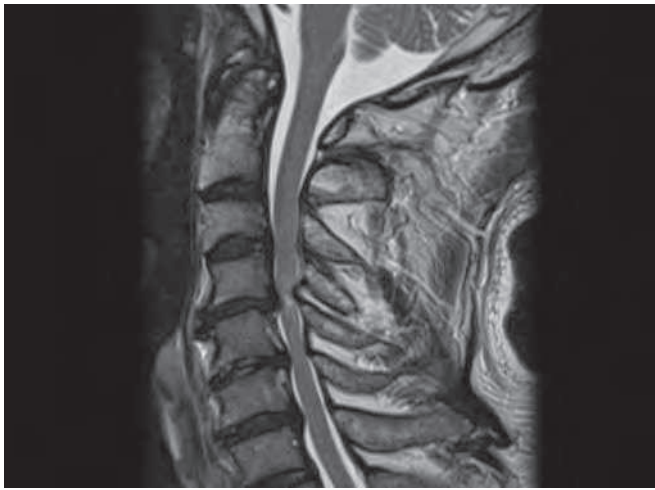


Fig. 6.8: Sagittal T2-weighted MRI showing spinal cord compression at the C4-5 intervertebral level and a high-intensity signal change.

history of trauma. On admission, neurologic examination revealed hypesthesia and hypalgesia below the forearms in the C6 dermatomes and bilateral biceps weakness. Biceps tendon reflexes were normal, triceps tendon reflexes were hyper-reflexive, and Hoffmann's reflex was present bilaterally. Sagittal T2-weighted MRI showed spinal cord compression at C4–C5 and C5–C6 from ligamentum flavum hypertrophy (Fig. 6.8). An area of high-signal intensity was observed in the spinal cord at the C4–5 level. The patient underwent a C3–C7 laminoplasty. MN-SCEPs, TES-SCEPs, and SC-SCEPs were recorded intraoperatively. Abnormalities were observed in all SCEPs at the C4–5 intervertebral level (Fig. 6.9).

KEY POINTS

- Postganglionic axon lesions (the plexuses and more peripheral nerves) cause sensory fibers to degenerate distally from that point, resulting in low-amplitude SNAPs or a failure to elicit SNAPs.
- Many electromyographers are able to diagnose radiculopathy and entrapment neuropathy with needle EMG abnormalities in a myotomal distribution.

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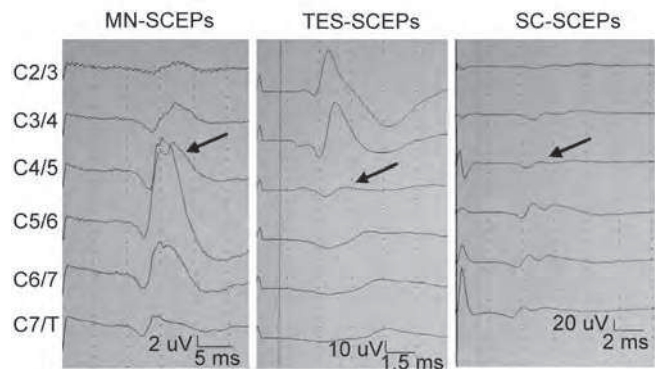


Fig. 6.9: Abnormalities were observed in all spinal cord-evoked potentials at the C4-5 intervertebral level (arrows).

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A five-pole recording electrode was placed in the cervical epidural space. The stimulation sites were the thoracic epidural space for conductive SCEPs, the median nerve at the elbow for segmental SCEPs. New findings, which could not be observed by roentgenograms, myelography, and CT scan, were detectable using this technique.

Satomi K, Okuma T, Kenmotsu K, et al. Level diagnosis of cervical myelopathy using evoked spinal cord potentials. *Spine.* 1988;13:1217-24.

The SCEPs resulting from both median nerve and spinal cord stimulation were recorded from the interlaminar yellow ligaments posteriorly or intervertebral discs anteriorly on patients with cervical myelopathy in order to determine the most significant lesion in the spinal cord electrophysiologically. The normal MN-SCEPs consisted of P1N1 and N2(P2) deflections, while normal SC-SCEPs consisted of N1 and N2 deflections. With these techniques, the level diagnostic rates of primary lesions were 94.7% in posterior recordings.

Interventional Spinal Diagnostics and Therapeutics

Naresh Kumar, Pankaj Kandwal, Wong Hee Kit

Snapshot

- » Relevant Anatomy
- » Medication
- » Types of Needle and Needle Manipulation Technique
- » Diagnostic Spinal Interventions
- » Diagnostic and Therapeutic Spinal Interventions

INTRODUCTION

Low back pain affects 70–85% of adults at least once in their lifetime.^{1,2} Neck pain is also common in the adult general population, with typical 12-month prevalence estimates from 30% to 50%.^{3,4} Both low back pain and neck pain comprise axial pain, which is rampant in present society due to increasing life expectancy and sedentary lifestyle. Men and women are equally afflicted by axial pain.⁵

Axial pain may be associated with radicular pain in some common conditions that include disc herniation, degenerative disc disease, facet disease, instability, spondylolisthesis, and other miscellaneous conditions. Acute spinal pain of a nontraumatic origin has a good prognosis for spontaneous recovery when it is not associated with significant neurologic deficits. One-third of the patients typically recover within 1 week, whereas two-thirds recover within 2 months. With respect to those with disc herniations and spinal pain, only 10% experience pain beyond 6 weeks.⁶ Majority of the patients can be treated successfully with nonoperative measures including rest and physical modalities of treatment and rehabilitation. However, a small proportion of patients with neck and back pain will not respond to these conservative measures and will continue to experience discomfort beyond 3 months and about 1.2% remain disabled by the end of a year.⁷

These selected groups of patients with disabling axial and/or radicular pain would require diagnostic evaluation. The diagnostic ladder for evaluation of such patients has been elucidated by Carragee and Cohen.⁸ The “primary diagnostic evaluation” usually involves screening for “red flags” by history and clinical examination. If this evaluation is negative, patients are put on nonoperative treatment as mentioned above. Patients who do not recover good function in due course undergo “secondary diagnostic evaluation.” This evaluation identifies serious psychological barriers to recovery and definitely rules out conditions that may result in neurologic injury or structural failure using appropriate imaging modalities. If primary and secondary evaluations fail to reveal a serious structural problem then a “tertiary diagnostic evaluation” is undertaken.⁸

In the absence of definitive diagnosis despite a thorough clinical examination, preliminary investigations, and magnetic resonance imaging (MRI), “special diagnostic tests” can be helpful in arriving at a conclusion. Isolating the source of pain can be a diagnostic challenge even with the available advanced imaging modalities. Interventional spinal procedures may constitute a major part of diagnostic armamentarium in the form of “special diagnostic tests” for locating the pain generator. In contrast to the mixed picture provided by history, physical examination,

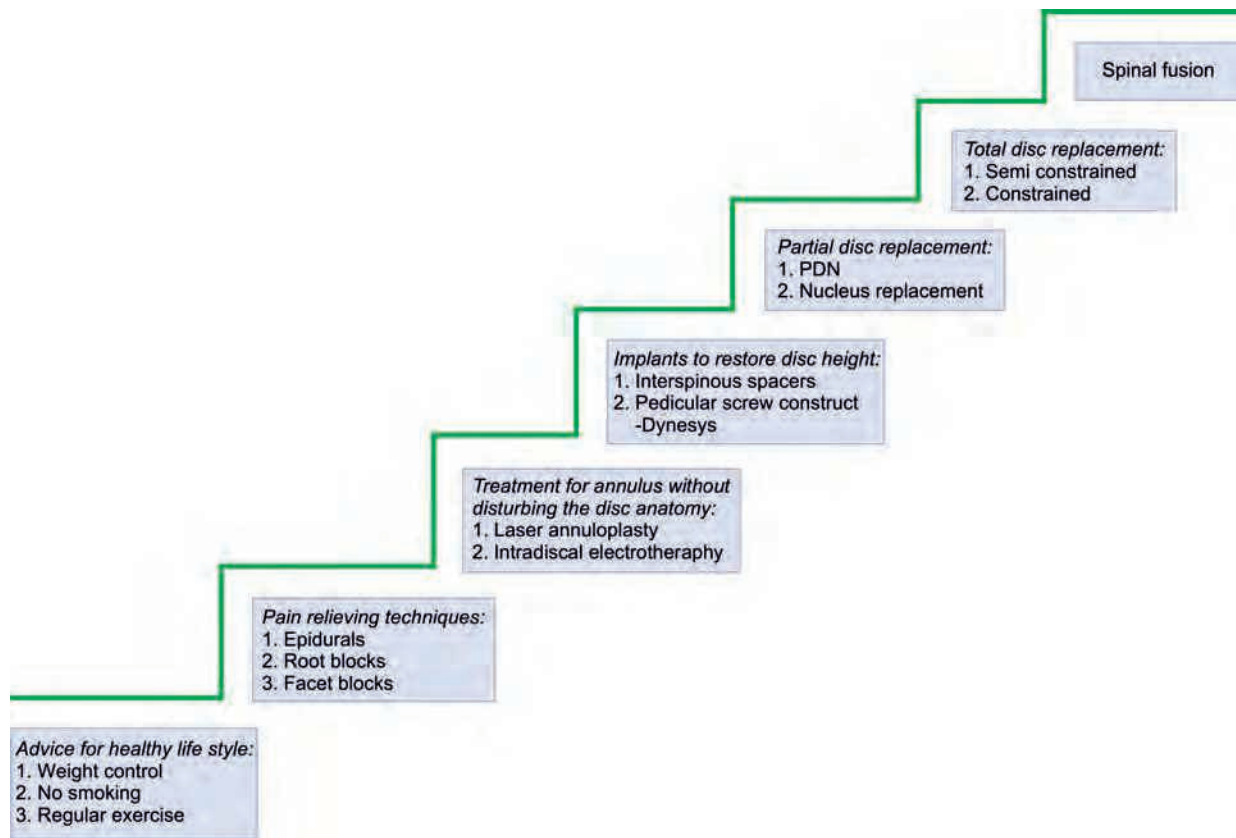


Fig. 7.1: Stepladder treatment plan for pain management for degenerative disc disease.

imaging, and nerve conduction studies in nonradicular pain, controlled diagnostic blocks have been shown to determine the cause of pain in as many as 85% of the patients while the other 15% were investigated with other available imaging modalities.⁴ Interventional therapeutics in the management of spinal disorders comes halfway between nonoperative modalities of treatment and definitive operative procedures. This is clearly highlighted by the therapeutic stepladder for the management of degenerative disc disease (Fig. 7.1).

In this chapter, we discuss the rationale and method of diagnostic procedures used to identify the source of axial pain syndromes in patients without serious underlying spinal pathologies such as infection and tumors. We also delve into therapeutic procedures to treat the same.

RELEVANT ANATOMY

Pain Generator Concept

The identification of the precise “pain generator” is a concept that is central to diagnostic evaluation and may influence

the choice of treatment. It is, however, controversial as some authors believe that the “pain generator” cannot be the sole factor in determining the seriousness and the disability associated with axial pain. The other determinants could be psychological or other neurophysiologic contributors. Despite thorough clinical examinations and advances in diagnostic technology, these “pain generators” may be difficult to identify.

Kuslich and colleagues⁹ studied 193 patients using local anesthetic (LA) to define and identify the pain source in these patients. They identified intervertebral discs, facet joints, ligaments, fascia, muscles, and nerve root dura as tissues capable of generating and transmitting pain in the low back region.⁹ The intervertebral disc, zygapophyseal joint, and sacroiliac joint are believed to be common pain generators in axial low back pain, with a reported prevalence of 5–39%,¹⁰ 15–40%,¹¹ and 6–13%,¹² respectively. Similarly, axial neck pain could have the pain source in the cervical disc, uncovertebral, facet joint, ligaments, fascia, and the muscles.^{13,14} We would like to highlight some major anatomical structures that can be classed as a primary pain source.

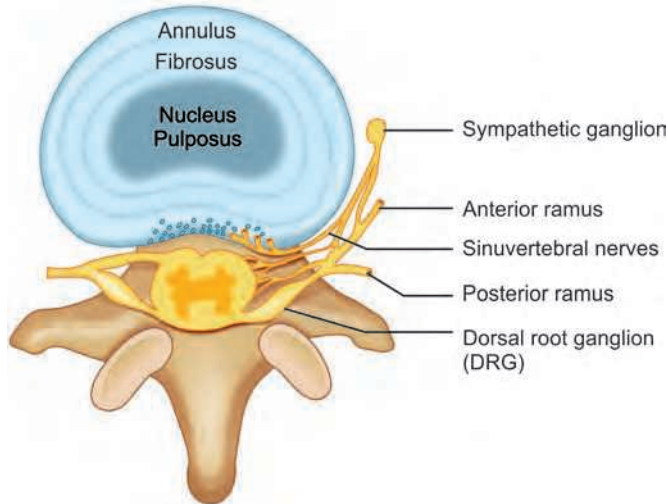


Fig. 7.2: Axial section at the level of intervertebral disc showing possible “pain generators.”

Intervertebral Disc

Intervertebral disc is richly innervated and hence could be the potential source of pain.¹⁵⁻¹⁷ The sinuvertebral nerves innervate the posterior aspects of the disc and the posterior longitudinal ligament. These nerves originate from one or two rami communicantes close to connection with the spinal nerves just distal and ventral to the dorsal root ganglion (DRG). The posterolateral aspects of the discs receive branches from adjacent ventral primary rami and from the grey rami communicantes near their junction with the ventral primary rami.¹⁵ The lateral aspects of the discs receive other branches from the rami communicantes. Some rami communicantes cross intervertebral discs and are embedded in the connective tissue of the disc deep to the origin of psoas. Such paradiscal rami are likely to be another source of innervation to the discs. The anterior longitudinal ligament is innervated by recurrent branches of rami communicantes¹⁵ (Fig. 7.2).

Dorsal Root Ganglion

Dorsal root ganglion is a unique component of the spinal nerve, containing the cell bodies of sensory neurons. The DRG is particularly sensitive to mechanical irritation and is suspected to be a key player in radicular pain syndromes. Because the DRG typically is located within the neural foramen, foraminal disc pathology or stenosis might be more likely to result in a burning or dysesthetic type of pain involving the affected limb¹⁶ (Fig. 7.2).

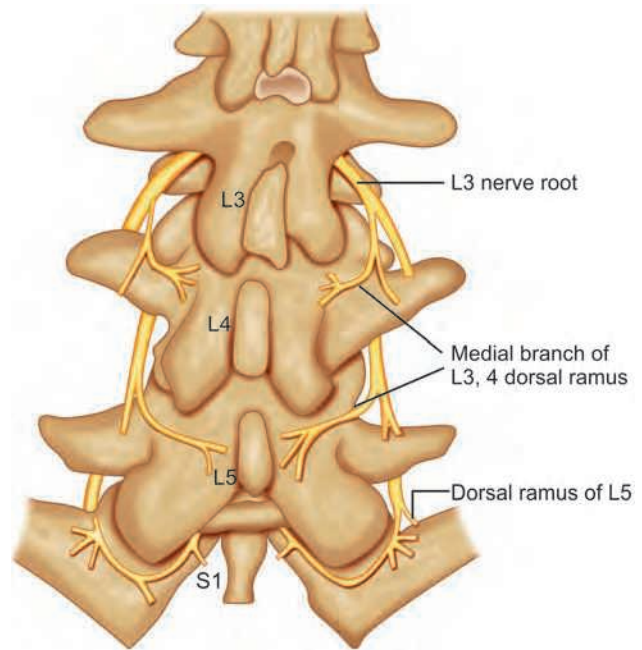


Fig. 7.3: Innervation of zygapophyseal joint.

Zygapophyseal Joint

Zygapophyseal joint is a synovial joint consisting of hyaline cartilage, synovial membrane, and a joint capsule. Capsule fibers blend posteriorly with the multifidus muscle and anteriorly with the ligamentum flavum. Two medial branches from consecutive vertebral levels innervate the cervical and lumbar zygapophyseal joints. Each medial branch courses over the respective transverse process one level above its origin.¹⁷⁻¹⁹ Dorsal root ganglion and the paravertebral sympathetic ganglion are extra innervation sources of the facet joint¹⁸ (Fig. 7.3).

Sacroiliac Joint

The innervation of the sacroiliac joint is under debate. Electrical and mechanical stimulation studies suggest that the innervation arises predominantly via the L4 to S1 nerve roots, with secondary contribution from the superior gluteal nerve.^{5,19}

MEDICATION

Steroids and local anesthetics are the cornerstone for diagnostic and therapeutic spinal injections, respectively. We hereby highlight some key features of these drugs, which would help our readers in choosing the medication.

Table 7.1: Corticosteroid preparations for spinal injections.

<i>Corticosteroid</i>	<i>Half-life (h)</i>	<i>Brand name</i>	<i>Description</i>	<i>Common dose (mg)</i>
Methylprednisolone acetate	12–36	Depo-Medrol	Particles densely packed; smaller than red blood cells; not prone to aggregation; contain benzyl alcohol (potentially neurotoxic); may not completely dissolve	20–80
Triamcinolone diacetate	12–36	Aristocort	Particles vary greatly in size; form aggregations	40–120
Triamcinolone acetonide	12–36	Kenalog	Particles vary greatly in size; form aggregations	40–80 (ESI) 20–40 (other sites)
Betamethasone acetate/ phosphate mixture	36–72	Celestone Soluspan	Particles vary greatly in size; form aggregations but are soluble	12–18 (ESI)
Dexamethasone	36–72	Decadron	Particles 5–10 times smaller than red blood cells; can aggregate	Variable

(ESI: Epidural steroid injection).

Steroids

Glucocorticoids are the group of steroids used for the management of pain disorders. The administration of corticosteroids is to offer therapeutic benefit in painful spinal conditions.

Mechanism of Action

The potential mechanisms include the following:

1. A direct membrane-stabilizing effect
2. Phospholipase A2 activity blockade
3. An anti-inflammatory effect, with inhibition of prostaglandin synthesis
4. Blockade of neuropeptide synthesis
5. Sympathetic blockade
6. Interruption of nociceptive input from somatic nerves
7. Blockade of C-fiber activity in the DRG
8. The mechanical effect of the injectant breaking up epidural adhesions.

The commonly used corticosteroid preparations are highlighted in Table 7.1.

The effectiveness of the corticosteroid depends upon its solubility, and the complications associated are dependent on particle size and the preservatives used. The question of neurotoxicity of the steroids arises from the vehicle polyethylene glycol and the preservative benzyl alcohol in the steroid preparation.²⁰ Other vehicles or preservatives in the steroids that can cause potential problems are methylparaben and sodium bisulfite.²⁰

Particulate versus

Nonparticulate Steroids

A particulate steroid is considered to be more effective than a nonparticulate one for spinal injections probably because of its local accumulative nature.²¹ However, particulate corticosteroids have a risk of embolic infarct, which can result in serious neurologic consequences or death.^{22–24}

Methylprednisolone, compounded betamethasone, and triamcinolone are particulates in nature, whereas betamethasone sodium phosphate is the only injectable steroid in pure liquid form and contains no particles apart from dexamethasone, but it is short-acting. The plausible explanation for the short duration of action is that soluble steroids are rapidly cleared from the spinal canal. Paul Dreyfuss et al.²⁵ in their study found that the effectiveness of dexamethasone was slightly lesser than that of triamcinolone, but the difference was neither statistically nor clinically significant.

In epidural steroid injections, the steroids are usually diluted with LAs and/or saline to decrease the concentration of benzyl alcohol and polyethylene glycol and to improve the spread of the drug. Benzon et al.²⁰ found that dilution did not decrease the size of the particles except in compounded betamethasone, in which increasing dilutions with the local anesthetic decreased the proportion of the larger particles. According to them, commercial betamethasone is the recommended preparation if a nonsoluble steroid is preferred. Similarly, Lee et al. also concluded that despite the potentially serious complications of particulate

steroids, such as embolic infarct, it is reasonable to use dexamethasone for cervical selective nerve root block (SNRB).²² Dexamethasone is a non-particulate steroid, but its routine use awaits further studies on its safety and efficacy.²⁰

Triamcinolone, on the other hand, has a smaller percentage of larger particles than methylprednisolone and compounded betamethasone and can be used if commercial betamethasone is not available. Triamcinolone has been considered superior to dexamethasone in various other studies.²¹ The authors also prefer using triamcinolone acetone for spinal injections.

Since the systemic effects of corticosteroids may persist for up to 2 weeks, repeat injections are advocated at least 2 weeks apart.

Local Anesthetic Medications

Two of the most commonly used local anesthetic (LA) agents in spinal injections are lidocaine and bupivacaine. Their mechanism of action is through dampening of C-fiber activity, and interruption of the nociceptive input and reflex mechanisms of the afferent limb of local pain fibers, thereby interrupting the pain-spasm cycle.⁵ Some investigators even suggest that these work on free glutamate released by herniated disc material.^{6,26} Several investigators have reported on the anti-inflammatory effect of local anesthetics, which is by inhibiting phagocytosis, decreasing phagocytic oxygen consumption, reducing polymorphonuclear leukocyte lysosomal enzyme release, and diminishing superoxide anion production.⁶ Local anesthetic agents may also reduce neural dysfunction in injured nerve roots.

The clinical action of LA is described in terms of potency, speed, and duration of action. The “potency” is related to their lipid solubility; hence the more lipophilic the LA agent, the more readily it permeates the neuronal membrane resulting in higher potency. Bupivacaine is nine times more potent than lidocaine. The “speed of onset” depends upon the dissociation constant and the pH of the local tissue. Lidocaine has greater speed of onset when compared to bupivacaine. The “duration of action” is dependent upon the site of injection, the presence of a vasoconstrictor, the lipid solubility, and the dose of LA. The more vascular the location the more rapidly the agent is absorbed, metabolized, and excreted. The duration of action of bupivacaine is twice as much as lidocaine for the same dose injected. The main features of the commonly used LA are summarized in Table 7.2

Table 7.2: Main features of the commonly used local anesthetics.

Agent	Available concentrations (%)	Onset	Duration (h)
Lidocaine	0.5, 1, 1.5, 2, 5	Fast	1–2
Bupivacaine	0.25, 0.5, 0.75	Slow	2–4

Adverse reaction related to LA is rare but grave, and hence clinical vigilance must be exercised. The adverse reactions are central nervous system or cardiovascular system toxicity apart from major allergic reactions.

TYPES OF NEEDLE AND NEEDLE MANIPULATION TECHNIQUE

In general, the needles used for spinal injections are straight with a beveled tip. All these needles are styled with an outer cannula that can be used to deliver medication or to accept a smaller diameter needle in a coaxial fashion. The common size of the outer needle is 0.9 mm (22G) and the inner needle, if used, is 0.45 mm (24G). The bevel in the needle facilitates directional needle placement—the needle tip tends to go in a direction slightly away from the bevel. The notch on the needle is on the same side as the bevel of the needle tip.²⁷ One can introduce a bend or bow on the needle shaft in order to increase the deflection of the needle when it is advanced for its placement. Minor deflection of the needle can be achieved by introducing a gentle bend in the distal part of the needle.²⁸ Regardless of the method of needle manipulation used, proper holding of the needle is critical in directing the needle to its intended target.²⁷

DIAGNOSTIC SPINAL INTERVENTIONS

Discography

Discography is an investigator-dependant diagnostic tool used for localizing the pain source. It is usually undertaken when surgical intervention is contemplated to localize the “pain generator.” The source of pain is apparent in pathologies such as infection, tumor, deformity, or instability; otherwise, there is an assumption that it is the anatomic structures leading to significant clinical axial pain. The speculations are further compounded by social and emotional characterization of pain.

Discography is performed after other imaging modalities such as radiography and MRI are exhausted and

they fail to localize the patient's symptoms. Provocative discography involves injection of a contrast agent into the nucleus pulposus of the disc in question, under fluoroscopic guidance. The results of the procedure are determined by assessing the patient's response to the contrast injection.

The term "discography" used to describe the study implies a strictly anatomic evaluation. However, there are several different components to provocative discography as commonly used in practice. For instance, the internal structure of the intervertebral disc may be evaluated by static and dynamic imaging studies during and after injection. The other key feature of the study is the assessment of pain provocation. The patient's subjective response to the injection of contrast into the disc is noted.²⁹

There are four important pieces of information obtained in an appropriately performed discography: the subjective pain response, the volume and/or pressure of the fluid injected into the disc (a normal disc accepts 0.5–2.5 cc), the morphology of the disc injected, and the lack of a pain response in the adjacent controlled disc levels tested.³⁰

Indications and Contraindications

Indications: The most common use of discography is to determine whether degeneration within a disc seen on imaging studies is the primary clinically significant source of a patient's low back pain illness.³¹ Indications^{32,33} for discography include, but are not limited to, the following:

1. To evaluate whether demonstrably abnormal discs correlate with the clinical symptoms
2. To assess patients with persistent, severe symptoms in whom other diagnostic tests have failed to reveal clear confirmation of a suspected disc as the source of pain
3. To consider patients who have failed to respond to surgical intervention so as to determine pseudarthrosis or possible recurrent disc pathology
4. To assess candidates for minimally invasive surgical intervention to confirm a contained disc herniation or to investigate the dye distribution pattern before chemonucleolysis or percutaneous procedures.

Contraindications: Contraindications^{32,34} to discography include, but are not limited to, the following:

1. Coagulopathy (international normalized ratio >1.5 or platelets <50,000/mm³)
2. Pregnancy (because of teratogenic effects of radiation)

3. Systemic infection or skin infection over the puncture site
4. Severe allergy to any component of the injection mixture (injectate) or other medication
5. A previously operated disc, which may yield a false-negative or false-positive result (and thus its evaluation may be difficult)
6. A solid bone fusion that does not allow access to the disc
7. Significant compression of the spinal cord at the level to be operated
8. Facetogenic, neoplastic, inflammatory, and traumatic pain has to be excluded before discography.

Protocol of Diagnostic Provocative Discography

The following protocols are suggested when provocative discography is contemplated.

Evaluation of the patient's symptoms: The levels at which discography is performed are based on the history provided by the patient with regard to the intensity of pain (visual analog scale scores), distribution and location of back or neck pain with associated appendicular pain, clinical examination, and imaging findings.

Technique of provocative lumbar discography

Position: We prefer the prone position as it allows better visualization of the lumbosacral junction. Fluoroscopy must be positioned with a cephalad tilt to allow end on visualization of the end plates. Thus, the disc space and the angle of entry into the disc can be clearly seen. At the lumbosacral junction, the C-arm may need to be tilted up to 45° for adequate visualization of the disc space.

Anesthesia: The procedure is carried out under adequate local anesthesia and minimal sedation. Adequate local anesthesia is necessary so that the patient is cooperative during the procedure, whereas minimal sedation ensures that he or she is conscious and coherent to answer questions about pain.

The back is painted with povidone iodine and draped. Lignocaine (2%) is infiltrated into the skin, the subcutaneous tissue, and the underlying musculature.

Contrast agent: We prefer Omnipaque 350 (GE Healthcare, Cork, Ireland), which is a low-osmolar, nonionic contrast agent for discography.



Fig. 7.4: Discography images for L4–L5, L5–S1.

Approach: For lumbar spine, the entry point is located by measuring approximately four fingers' breadth distance from either side of the midline at the desired disc level using fluoroscopic guidance. A coaxial two-needle oblique extradural approach is used. First, a 0.9-mm (22G) \times 125-mm needle is introduced at about 45° to the horizon. It is targeted to enter the disc lateral to the superior articular pillar (SAP), yet medial to the exiting nerve root. Once the tip of this needle is just hitched to the annulus, a longer needle with a smaller diameter—0.45 mm (25G) \times 150 mm—is railroaded through the first needle and inserted into the nucleus of the disc.

A thicker (0.9-mm), first needle is preferred as it provides stability and a steady path toward the disc. The tip of this 0.9-mm needle stops just at the outer layer of the annulus. Thereafter, a thinner (0.45-mm) and longer second needle is railroaded through the outer needle into the nucleus of the disc. A thinner needle causes less damage and is associated with a lower risk of triggering a degenerative response in the nucleus of the disc.

Placement of the tip of the needle in the center of the disc is confirmed under the C-arm to ensure that the injection of the contrast would not be into the annulus. The contrast agent is injected into the nucleus of the disc slowly, depending upon the resistance (Fig. 7.4). Distribution of the contrast agent within the disc is assessed under the C-arm to determine the disc morphology (Table 7.3) as follows.^{34,35}

Technique of provocative thoracic discography: Thoracic discography is not a commonly performed procedure. When indicated, it is performed with the patient

Table 7.3: Six types of discogram and stages of disc degeneration.³⁵

Imaging finding	Significance
1. Cotton ball	No degeneration, soft amorphous nucleus
2. Lobular	Mature disc with nucleus starting to coalesce into fibrous lumps
3. Irregular	Degenerated disc with fissures and rents in the nucleus and inner annulus
4. Fissured	Degenerated disc with radial fissures leading to the outer edge of the annulus
5. Ruptured	Disc has a complete radial fissure that allows injected fluid to escape. This can be at any stage of degeneration
6. End plate fracture	Disruption of end plate

in a prone position. Although the technique is not very different from lumbar discography, anatomical differences between the thoracic and lumbar spines must be borne in mind. Facet joint orientation varies with different levels of the spine. In the thoracic spine, the processes face posteriorly, whereas in the lumbar spine they face medially. For thoracic discography, the tip of the needle is aimed to a radiolucent rectangular space between the SAP and the costovertebral junctions under C-arm guidance.³⁴ This avoids contact with the thecal sac, pleura, or the spinal cord. Once the position of the needle is confirmed to be in the center of the disc, the contrast agent is injected.³⁶

Technique of provocative cervical discography: With the patient in the supine position, an anterolateral approach for cervical discography is used. The soft tissues on the right side of the neck and vascular structures are manually displaced laterally, whereas the esophagus and trachea are deviated medially. The carotid pulse is palpated. Under C-arm guidance, the discography needle is inserted between these structures via a right anterior oblique approach into the central part of the nucleus. Precaution to avoid carotid puncture must be taken.³⁴ After satisfactory placement of the needle into the desired disc space, the contrast agent is injected.

Pressure-controlled Manometric Discography

Manometry may be performed during discography to determine the opening pressure, pressure at the onset of pain, and maximum pressure. Opening pressure is noted when the dye is visualized in the disc space. The injection of

the contrast agent is continued into the disc until reaching 90 psi or until pain is elicited. If pain is elicited at pressures <15 psi, the disc is considered to be chemically sensitive. A chemically sensitive disc is highly sensitive, which does not require increased pressure to provoke pain. If pain is elicited between 15 and 50 psi, the disc is considered to be mechanically sensitive. If pain is elicited between 51 and 90 psi, other sources of pain must be looked into. If no pain is provoked by 90 psi, the disc is considered to be negative. With the use of pressure-controlled manometric discography, improved and more specific diagnostic categorization of positive discography results is possible. Precise prospective categorization of positive discographic diagnoses may predict outcomes from treatment, surgical or otherwise, thereby greatly facilitating therapeutic decision making.^{37,38} Rapid injection of the contrast media may result in discrepancy between the real intradiscal pressure and the manometric pressure.³⁹ Automated pressure-controlled discography systems help inject contrast at a slow and constant rate. It is believed that automated discography helps validate the contents of discography and contributes to accurate interpretation of discography results. In addition, it may lower false-positive or negative responses compared to conventional discography.⁴⁰

CT Discography

If computed tomographic (CT) discography is contemplated, CT must be performed immediately after discography. It helps further assess annular degeneration and disruption.

Rate of False-Positives in Discography

In a study on 26 subjects with no low back symptoms, Carragee et al.⁴¹ found that the rate of false-positive discography may be low in subjects with normal psychometric profiles and without chronic pain. However, significantly painful injections were very common in subjects with annular disruption and chronic pain or abnormal psychometric testing.⁴¹ Patients with significant comorbid psychological conditions and/or secondary gain issues should not be subjected to discography due to ample evidence of false-positive findings in these patients.³⁴

However, in a systematic review of lumbar provocative discography in asymptomatic subjects with a meta-analysis of false-positive rates, Wolfer et al. obtained a specificity of 0.94 (95% confidence interval, 0.89–0.98) and a

false-positive rate of 6%. They concluded that contrary to recently published studies, discography has a low false-positive rate for the diagnosis of discogenic pain.⁴²

The patient's response to the contrast injection is assessed by asking the following questions:

- Is there pain? Feeling of sensation of pressure after the contrast injection does not equate to pain.
- What is the nature of pain? Is it similar to the kind of back pain you usually have?
- What is the distribution of pain? Does the provoked pain cover the same area as the usual pain (concordant) or a different one (discordant)?
- What is the intensity of pain on the visual analog scale?

The result is considered positive if the provoked pain is concordant, similar in nature to the usual pain and $\geq 6/10$ in intensity. The results may be compared against a control disc (morphologically normal disc on MRI). We prefer injecting the control disc before injecting the disc level in question. However, it is important that the patient is not aware of the level injected, the volume injected, and the moment of injection in order to improve the validity of the pain response. Nonpainful discs with positive imaging findings are not considered significant.

Complications

Many of the serious complications and high complication rates reported previously have decreased because of improvement in injection technique, imaging, and contrast materials.³³ Discitis is a serious complication after discography. Strict aseptic precautions during the procedure and the use of two-needle technique help reduce the incidence of discitis.^{33,43} The role of prophylactic antibiotics in prevention of discitis is controversial. Although it was previously believed that prophylactic antibiotics help reduce the incidence of discitis,^{44,45} Willems et al.⁴⁶ concluded that the risk of discitis after two-needle discography is minimal and does not justify their routine use.

Sometimes, the discography needle may brush past a nerve root, causing pain that may last for a few days. Other complications include transient exacerbation of pain and rarely, an epidural abscess. Quadriplegia and carotid artery injury are potential risks associated with cervical discography.

It was previously thought that discography may put the disc at risk of premature degeneration. However, in a study of roentgenographic changes in 188 patients at follow-up evaluations of 10–20 years, Flanagan and Chung⁴⁷

concluded that discography did not cause degenerative changes in the disc. In contrast, in a prospective, 10-year, matched cohort study, Carragee et al.⁴⁸ concluded that modern discography techniques even with the use of a small-gauge needle and limited pressurization resulted in accelerated disc degeneration, disc herniation, loss of disc height and signal, and the development of reactive end plate changes, compared with matched controls. A careful consideration of risks and benefits should be used in recommending procedures involving disc injection.

According to Boswell et al.,⁵ the evidence for cervical and thoracic discography is limited. The evidence for lumbar discography is strong for discogenic pain provided that lumbar discography is performed based on the history, physical examination, imaging data, and analysis of other precision diagnostic techniques.

■ DIAGNOSTIC AND THERAPEUTIC SPINAL INTERVENTIONS

Facet Joint Injection and Medial Branch Block

Diagnostic blocks of a facet or zygapophyseal joint can be performed by anesthetizing the joint by injections of local anesthetic/steroid intra-articularly or on the medial branches of the dorsal rami that innervate the joint, to evaluate whether the facet joint is the source of pain.⁵

The C2–3 and C5–6 facet joints are the most commonly affected segments in cases of cervical facet-mediated pain diagnosed by facet joint blocks.⁴⁹ Similarly, L4–L5 and L5–S1 are more commonly attributed to have lumbar facet pain. Pain from facets is characteristically unilateral, in the cervical spine radiating from the occiput to the nape of neck, shoulder blade, and upper back region whereas in the lumbar spine it may radiate into the buttocks up to the posterior thigh.

*Technique*⁵⁰

The patient is placed prone on the fluoroscopy table, with a pillow under the abdomen to reduce the lumbar lordosis. The overlying skin is prepared and the C-arm is rotated until the facet joint space is first seen. This renders the beam parallel to the posterolateral part of the joint, which is accessible for direct puncture. A 22-gauge spinal needle (3½ or 5 inches) is placed on the skin so that the tip is projected over the inferior part of the joint. Using the

needle tip as a marker, 5–10 mL of 1% lignocaine is injected into the skin and subcutaneous tissue. Care is taken to keep the hypodermic needle and syringe parallel to the X-ray beam. The syringe is disengaged, leaving the needle to act as a guide for the entry point and direction of the spinal needle. The latter is then introduced parallel and as close as possible to the hypodermic needle, aiming at the inferior recess of the joint, until passage through the capsule is felt and a bony end point is reached. In case technical difficulty of entering the joint is encountered, the superior recess of the joint is the second preferred site for needle insertion. Joint entry is confirmed by instillation of 0.1–0.2 mL of the nonionic contrast agent (Omnipaque), which collects in the superior and inferior recesses of the joint, giving a characteristic appearance of a seahorse on the fluoroscopy image (“seahorse sign”). Subsequently, 2 mL of 0.5% bupivacaine is injected for diagnostic purposes or 1 mL of 0.5% bupivacaine and 1 mL of triamcinolone for therapeutic purposes.⁵⁰

Intra-articular Blocks versus “Medial Branch Blocks”

Intra-articular injections are often more difficult and time consuming than medial branch blocks (MBBs) because they require access to the joint space, which may be extremely difficult or impossible in a degenerated facet joint, and care has to be taken that injection does not rupture or overly distend the joint.^{6,51} The medial branch block, in contrast, requires anesthetizing both of the medial branches that innervate the target joint.⁵ Significant leakage of intra-articular injected fluid into the epidural space and spillage over to the nerve roots have been described, which reduces the diagnostic accuracy of facet blocks. With appropriate care, this spillage is minimized with the MBB improving its precision. Finally, intra-articular blocks are appropriate if intra-articular therapy is proposed, but if radiofrequency therapy is proposed, MBBs become the diagnostic procedure of choice.⁵

The diagnostic and therapeutic results between the two techniques (i.e. intra-articular vs MBB) have been comparable,⁵² and both are associated with significant rates of false-positives and negatives.⁵³ The false-negative response rate of MBBs has been reported to be 11%.⁵⁴ Although diagnostic blocks are associated with a false-positive rate reported to vary between 25% and 45%, most investigators believe that a positive response of at least 50% improvement in clinical symptoms should be documented compared to prediagnostic MBB.^{55–57} Other investigators prefer a response of at least 80% improvement.^{58–61}

Facet Denervation

Facet denervation is a procedure by which a discrete lesion is created on the medial branches of the dorsal rami that innervate a facet joint. Although techniques such as cryoneurolysis and laser denervation have been performed, radiofrequency thermal-mediated ablation of the medial branch is the mainstay of facet denervation techniques.⁶

A major source of controversy is whether to perform confirmatory blocks before lumbar facet joint denervation. All the guidelines and commissioned position papers endorsed by major spine and interventional pain societies recommend using double blocks to screen patients for facet joint denervation. On the other hand, Cohen et al. in a multicenter analysis concluded that the degree of pain relief obtained after diagnostic screening blocks does not correlate with zygapophyseal joint denervation outcomes.⁶²

Epidural Steroid Injections

Direct epidural injection of corticosteroids for the treatment of cervical and lumbar spinal pain syndromes was first described in 1952.⁶³ The mechanism by which epidural steroid injection works is uncertain. The likely explanation for the action is the volume of injectate aids in lysis of adhesions and/or clears inflammatory exudates from the target neural structures by dilution.⁶ Three different routes used for delivery of medications to the epidural space are as follows:

1. Caudal
2. Interlaminar
3. Transforaminal.

Caudal

Caudal epidurals are considered as the safest and easiest, with minimal risk of inadvertent dural puncture, even though requiring relatively higher volumes of drugs.^{4,64} In the past, caudal epidural injections have been shown to be effective when compared with interlaminar epidural injections.^{4,65,66} However, the recent literature has shown that caudal epidural injections may not be superior to either interlaminar or transforaminal, but they may provide equal effectiveness.^{4,65,67}

Interlaminar

The interlaminar approach involves insertion of the epidural needle midway between the laminae of adjacent vertebrae.

The drug through the interlaminar route is often deposited on the dorsal aspect of the cord/thecal sac. It is conjectured that dorsal deposition of the drug may not reach the pain source that is usually located ventral to the thecal sac.

Transforaminal

Transforaminal route may be more effective than interlaminar or caudal techniques, possibly because of a higher incidence of steroid placement in the ventral epidural space.⁶⁸

Although SNRBs and transforaminal injections are often used interchangeably, purists insist on describing these as separate and distinct techniques.⁶ In the transforaminal injection, needle placement is more inferior to the nerve root and medial as compared to nerve root blocks.

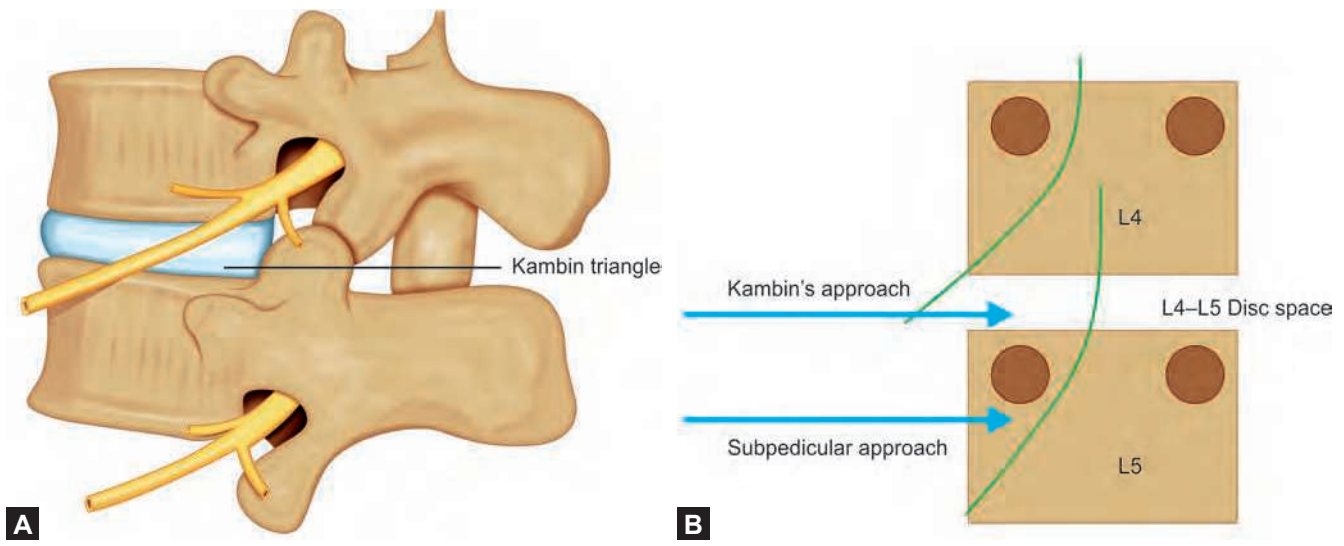
Efficacy of SNRBs is also dependent on the type of pathology causing spinal radicular pain. Strobel and colleagues⁶⁹ found that patients with cervical foraminal disc herniation and resultant foraminal compromise had better pain relief than those with superimposed spinal stenosis. Similar findings were seen in selective nerve root injections in the lumbar spine for radicular pain caused by disc herniation versus spinal stenosis.⁷⁰ Lutz and colleagues found that patients with moderate to severe lateral recess stenosis responded less favorably to selective nerve root injections and were more likely to require subsequent surgery.⁷¹ In a systemic review, Manchikanti et al.⁷² concluded that the evidence is good for the treatment of radiculitis secondary to disc herniation with local anesthetics and steroids and fair with local anesthetics only; it is fair for radiculitis secondary to spinal stenosis with local anesthetics and steroids. For epidural steroid injection, Chou et al.⁷³ found fair evidence of moderate benefit compared with placebo injection for short-term pain relief in patients with radiculopathy.

Selective Nerve Root Block

Neck/back pain with radicular symptoms is due to nerve dysfunction, which can result from mechanical compression either by prolapsed disc/an osteophyte or by nerve root inflammation with numerous proinflammatory cytokines implicated in causing chemical irritation, “chemical radiculitis,” including phospholipase A2, metalloproteinases, interleukin-6, prostaglandin E2, and tumor necrosis factor.^{5,16}

Diagnostic Nerve Root Block

The value of diagnostic SNRBs in the preoperative evaluation of patients with negative or inconclusive imaging



Figs. 7.5A and B: Diagrammatic presentation of “safe triangle” or “Kambin triangle.”

studies and clinical findings of root irritation was reported in 1971 by Macnab.⁷⁴

Diagnostic selective nerve block is typically performed in a patient with persistent pain when history, examination, imaging, and other precision diagnostic injections and electrophysiologic testing do not identify the pain generator. The reported sensitivity of a diagnostic SNRB ranges from 45% to 100%.⁵ There is limited evidence on the effectiveness of selective nerve root injections as a diagnostic tool for spinal pain.⁷⁵ A variety of names have been given to this procedure: SNRB, selective nerve root sleeve injection, selective epidural, selective spinal nerve block, selective ventral ramus block, and periradicular injection.

“Safe triangle” or “Kambin triangle” (Figs. 7.5A and B): Kambin triangle is defined as a right triangle over the dorsolateral disc. The hypotenuse is the exiting nerve root, the base (width) is the superior border of the caudal vertebra, and the height is the dura/traversing nerve root.⁷⁶

Indications:⁷⁷ Indications for periradicular spinal injections include, but are not limited to, the following:

1. Patients with known cause for pain who benefit by temporary pain relief (e.g. disc prolapse, foraminal stenosis, and degenerative disc disease with nerve root irritation)
2. Patients with multilevel imaging abnormalities, to more accurately defining the levels for possible surgery (i.e. for surgical planning)
3. Patients with equivocal neurologic examination

4. Patients with symptoms but minimal or no definitive imaging findings
5. Postoperative patients with unexplainable or complex recurrent pain.

Contraindications:⁷⁷ Contraindications for periradicular spinal injections include, but are not limited to, the following:

1. Coagulopathy (international normalized ratio >1.5 or platelets <50,000/mm³)
2. Pregnancy (because of teratogenic effects of radiation)
3. Systemic infection or skin infection over the puncture site
4. Severe allergy to any component of the injection mixture (injectate) or other medication
5. The patient received the maximum amount of steroids allowed for a given period unless the injection is performed without steroids
6. A solid bone fusion that does not allow access to the nerve root foramen
7. Significant compression of the spinal cord (thoracic and cervical region) at the level to be injected.

We hereby describe the procedure of fluoroscopic-guided periradicular injections for the lumbar, cervical, and thoracic spines (Table 7.4).

Medication:⁶ Diagnostic injectate is bupivacaine hydrochloride 0.25% 0.5–1 mL and therapeutic injectate is a combination of bupivacaine hydrochloride 0.25% 0.5–1 mL and triamcinolone acetonide 1 mL (40 mg/mL).

Table 7.4: Equipment required for fluoroscopic-guided periradicular injections for lumbar, cervical, and thoracic regions.

<i>Equipment/supplies</i>	<i>Details and specifications</i>
Spinal needle (Steriseal–Unomedical, UK)	22G, 5.0 inches (lumbar) 22G, 3.5 inches (thoracic and cervical)
Spinal needle (Steriseal–Unomedical, UK)	25G, 6.0 inches (lumbar) 25G, 4.0 inches (thoracic and cervical)
Syringe 5.0 mL	Containing injectate (local anesthetic and steroid)
Syringe 2.5 mL	Containing noniodinated myelographic contrast medium (Omnipaque 350° GE Health- care, Cork, Ireland)
Syringe 10 mL	With 23G 1.5-inch needle containing 10 mL of 1% ligno- caine for local anesthesia for skin infiltration
Miscellaneous	Sterile gauze, povidone-iodine scrub, alcohol scrub, sterile towel and drapes, lead apron, C-arm (Phillips BV Libra or Siemens Arcadis Orbic)

Preprocedural assessment: Allergy to the contrast agent must be evaluated by the clinician. In cases of severe iodine contrast allergy, gadolinium and saline have been suggested as options.³⁴ Renal impairment has also to be taken into consideration before the administration of contrast agents. It is still possible to perform the procedure without intravenous contrast medium enhancement, but it is more difficult. Analgesic and anti-inflammatory medications must be stopped on the day of the procedure to avoid any likely interference to the perception of pain during the procedure. Informed consent must be obtained.

Lumbar Periradicular Injection

Patient position: We prefer the prone position as it allows better visualization of the lumbosacral junction and there is no need for any side supports or restraints to support the patient during the procedure. The fluoroscopic C-arm must be positioned with a cephalad tilt to allow end-on visualization of the end plates and pedicles at the level where the injection is to be carried out. At the lumbosacral junction, the fluoroscopic C-arm may need to be tilted up to 45°

for adequate visualization of the disc space. The patient's lower back is prepared and draped in a sterile fashion.

Approach for L1 to L4 SNRBs: For the lumbar spine, the entry point is located by measuring approximately four fingers' breadth distance from either side of the midline at the desired disc level using fluoroscopic C-arm guidance taking images in the anteroposterior and lateral plane. A coaxial two-needle, oblique extradural approach is used. First, a 0.9-mm × 125-mm needle is introduced at about 45° to the horizon. It is targeted to reach dorsal to the nerve root or in the axilla of the nerve root depending on the requirement. For lumbar nerve roots L3 and L4, the needle is advanced to a point just inferolateral to the pedicle until radicular pain is elicited. For L1 and L2 (and T9 to T12), the needle is positioned more inferior and lateral in relation to the pedicle (in the inferior neural foramen) to decrease the risk of injury to the artery of Adamkiewicz. Often, the needle must be passed until it makes contact with the vertebral body. If radicular pain is not elicited, the needle is repositioned a few millimeters away until radicular pain is reported. Once the tip of this needle is just proximal to the site of the desired position, a smaller-diameter longer needle (0.45 mm × 150 mm) is railroaded through the first needle such that it emerges in a suitably close position to the nerve root. A thicker (0.9-mm) first needle is preferred as it provides stability and a steady path toward the spinal column. Thereafter, a thinner (0.45 mm) and longer second needle is railroaded through the outer needle in the periradicular space. A thinner needle causes less damage and is associated with a lower risk of nerve root injury.

It is important to realize that the artery of Adamkiewicz (arteria radicularis magna) enters the spinal canal through the neural foramen near the DRG. This artery, which is the main supply to the lower two-thirds of the spinal cord, arises from a segmental artery from the aorta and enters the spinal canal anywhere from T7 to L4. The typical location of the artery of Adamkiewicz is on the left (approximately 80%) from T9 to L1. The artery usually enters in the superior or middle portion of the neural foramen, slightly ventral and superolateral to the DRG.⁷⁷ Therefore, with the lower thoracic and upper lumbar SNRBs (and particularly left-sided SNRBs at these levels), we prefer to block the nerve slightly more inferolaterally in relation to the pedicle.

Up to 1 mL of contrast is injected, and the needle position is confirmed with the help of C-arm imaging and

also by patient response. The injectate is then injected for therapeutic or diagnostic purposes.

Approach to L5 SNRBs: Patient positioning and C-arm rotation are similar to the aforementioned approach. Often the area in which the needle has to be passed is a triangular window formed by the inferior margin of the transverse process of L5, the superior articulating process of S1 and the iliac crest. However, with standard positioning, the iliac crest may completely obstruct the approach. If one is not able to achieve a position that places the superior articular facet at the midpoint of the vertebral body, one obtains the best possible angle that allows visualization of the upside-down triangle. In this case, needle insertion is performed from a lateral to medial direction to pass medial to the iliac crest with the tip of the needle projecting inferior to the pedicle. For the L5 nerve root, the needle is advanced parallel to the X-ray beam through the center of the triangle until radicular pain is achieved. If radicular pain is not elicited, the needle can be repositioned or, if necessary, the C-arm can be repositioned a few degrees in all directions. Once again, the vertebral body forms the backdrop for the triangle so that the vertebral body limits the depth of needle penetration.

Approach to S1 sacral SNRBs: The C-arm can usually maintain with a caudocranial angulation of the X-ray beam (image intensifier above the patient, obliqued toward the patient's head), so that the X-ray beam is either in the straight anteroposterior (AP) projection or with at most 5–10° of ipsilateral lateral angulation. The S1 sacral foramen is seen as a round lucency in the upper sacrum. For the S1 nerve root injection, the needle is placed until it contacts one of the bone margins of the sacral foramen. The needle is then advanced into the foramen a few millimeters until radicular pain is elicited. When the needle tip touches the nerve root, the patient generally reports intense pain in S1 distribution. If this pain is concordant with the patient's typical pain distribution, 0.5–1.0 mL of the nonionic myelographic contrast medium may be injected to confirm the needle position in the nerve root sheath (this step is optional). There is no depth indicator for sacral needle placement. Therefore, one must be careful not to pass through the foramen into the pelvis, and so it is important to monitor the needle trajectory in AP and lateral planes for S1 injections.

Assessing proper needle position for the lumbosacral levels: Regardless of the level injected, depth of the needle penetration should be evaluated periodically with lateral fluoroscopy. Intermittent gentle negative aspiration should

be performed during the injection to make sure that the needle tip has not entered a vascular structure. Injection of contrast agent is performed for several reasons:

1. It will indicate whether the needle is properly in the nerve root sleeve and not within the nerve root itself. Injection of the nerve root directly can cause severe, sustained radicular pain, which should be avoided if possible.
2. Contrast agent injection will also confirm that the needle is not positioned within a vascular structure, a situation that would remove the injectate from the injection site and negate any diagnosis or therapeutic benefit. Also, if the needle was placed within a vascular structure, a therapeutic injection with a particulate steroid could also result in vascular occlusion or thrombosis. In the case of the artery of Adamkiewicz, this could lead to spinal cord infarction.

The argument against contrast agent injection is that the patient experiences continuous radicular symptoms while the contrast agent is being injected. In practice, the time between contrast agent injection and nerve root block is relatively short.

Once proper needle position has been established, the injectate (diagnostic or therapeutic) is instilled into the nerve root sleeve. This is done slowly to minimize the amount that might flow retrograde into the epidural space, which would make the injection less specific. The needle is then removed. The patient's skin is then cleansed and an adhesive bandage is applied to the puncture site.

Cervical Periradicular Injection

Author's preferred technique¹³

Patient positioning: The patient is placed in the lateral position on the operating table, with the symptomatic side facing up. One or two pillows are placed under the head to prevent lateral flexion of the cervical spine. The neck is slightly extended and the patient is requested to depress both shoulders. This position helps to visualize the entire cervical spine in the majority of patients.

Approach: The fluoroscopic C-arm is centered on the relevant level and tilted by 20–30° in order to obtain oblique projections of the cervical spine. This would show the neural foramen end-on. A metallic ruler is placed transversely on the patient's neck, so that it projects at the upper border of the nerve root foramen of the level to be injected and parallel to the disc space. A horizontal line is drawn on the skin at

this level. A vertical line is drawn joining the posterior borders of the lateral masses of the adjacent vertebrae. Intersection of these lines gives us the entry point for the needle, which overlies the bulk of the trapezius muscle and falls in the posterior triangle of the neck.

The injection site is aseptically prepared and LA (2% lignocaine, Xylocaine, AstraZeneca, UK) is infiltrated into skin and subcutaneous tissues. For the “two-needle technique”, we use a 0.9-mm × 100-mm needle as the “outer needle” and a 0.45-mm × 125-mm needle as the “inner needle” (Steriseal-Unomedical, UK). The outer needle is well suited to negotiate the skin, deep fascia, and muscle layers without bending. The 0.9-mm needle with stylet is introduced through the entry point on the skin and directed using image guidance through the bulk of the trapezius muscle, keeping it posterior to the neurovascular bundle of the neck. The needle is advanced under image guidance until the tip of the needle is just anterolateral to the posterior border of neural foramen, without actually entering it. An AP view is also obtained at this stage. The stylet is removed and the inner needle is inserted through the lumen of the outer needle. The inner needle is advanced with caution, to enter the nerve root canal under image guidance, observing the patient’s response. In a majority of patients, radicular pain is reproduced at this point, which usually matches their clinical symptoms. Aspiration is attempted with a 5-mL syringe to ensure that the needle tip is not in any blood vessel. Up to 0.2–0.5 mL of the radio-opaque dye (Iopamidol, Niopam 200 Bracco UK Ltd) is injected through the inner needle to obtain an epidurogram, showing spread of the contrast medium along the nerve root. A hard copy of the epidurogram is printed for record. A mixture of 1 mL of long-acting steroid (40-mg triamcinolone acetonide, Kenalog-Squibb UK) and 0.5–1 mL of long-acting LA (0.25% bupivacaine, Marcaine, AstraZeneca, UK) is injected through the needle into the periradicular space. The patient is observed for 1–2 hours after the procedure and then discharged.

Pulsed Radiofrequency

At present, most studies indicate that the mechanism of action in the pulsed radiofrequency (PRF) procedure is an alteration in synaptic transmission, in a neuromodulatory-type effect.^{78,79} In general, there are two types of PRF procedures. The first category is intermittent radiofrequency procedures, such as the thermocoagulation of the medial branch. In this category, the potential contribu-

tion of PRF would probably be modest at best. Even if PRF were equally effective as thermal or conventional radiofrequency, the impetus to adopt PRF would lie in a significant reduction in complications or side effects. The second types of procedures are where continuous radiofrequency is used and it has limited indications. This includes PRF treatment for peripheral neuropathies, arthrogenic pain, painful trigger points, and PRF application of the DRG in patients with neuropathy or radiculopathy.

Chua et al.⁷⁹ in a review of randomized controlled trials (RCTs) concluded that evidence for the use of PRF to the DRG in cervical radicular pain is compelling. With regard to its lumbosacral counterpart, the use of PRF cannot be similarly advocated in view of the methodological quality of the included study. The use of PRF in lumbar facet arthropathy was found to be less effective than conventional radiofrequency thermocoagulation techniques.⁷⁹

Sacroiliac Joint Injections

Sacroiliac joint is formed by the articulation between the sacrum and the ilium. It has two parts, the inferior half to two-thirds of the true synovial lined cartilaginous joint and a fibrous articulation superiorly. The sacroiliac joint is attributed as a potential source of low back and/or buttock pain with or without lower extremity pain. The biggest challenge in coming to a diagnosis of sacroiliac pathology is identifying pain arising from sacroiliac joint and also assessing the contribution of the sacroiliac joint to the pain. Certain provocative test described may help us identify the sacroiliac source of pain.^{80–82}

The validity of sacroiliac joint block has been established by injecting small volumes of LA with contrast into the joint and determining contrast spread posteriorly into the dorsal sacral foramina, anteriorly into the lumbosacral plexus and superior recess extravasation at the sacral alar level along the fifth lumbar epidural sheath in radiographs.^{5,83} Construct validity of sacroiliac joint blocks has been established by determining the false-positive rate of single, uncontrolled, sacroiliac joint injections of 20% and 22%.^{84,85} False-positive responses may occur with extravasation of the anesthetic agent out of the joint due to defects in the joint capsule. False-negative results may occur from faulty needle placement, intravascular injection, or inability of the local anesthetic to reach the painful portion of the joint due to loculations. Several authors have shown the sacroiliac joint to be a source of pain in 10–30% of cases by a single-block¹² and 10–26.6% by a double-block paradigm.^{84,85}

The evidence is good for the diagnosis of sacroiliac joint pain utilizing controlled comparative local anesthetic blocks. The evidence for provocative testing to diagnose sacroiliac joint pain was fair. The evidence for the diagnostic accuracy of imaging is limited.⁸⁶

Technique

The patient is placed prone on the fluoroscopy table, with the hip and pelvis raised to 20–30°. This places the joint parallel to the X-ray beam, which is pointed directly down. It also exposes the synovial portion of the joint, allowing passing the needle vertically down. The varying obliquity of the joint will necessitate somewhat diverse degrees of tilt in different patients. Injecting small amount of contrast (0.2–0.5 mL) material will confirm the position of the needle. In addition, the contrast agent may have diagnostic implications by identifying abnormalities in articular contour, collections of juxta-articular fluid, or synovitis.⁸⁷

Intradiscal Electrothermal Therapy/ Radiofrequency Ablation/Nucleoplasty/ DiscFx

Intradiscal Electrothermal Therapy

Internal disc disruption, annular tear, and degenerated disc disease are a spectrum of the same disease leading to discogenic back pain. Discogenic pain is attributed to irritation of the small nerve endings within the annulus fibrosis. Heat was first used to treat discogenic low back pain in 1996, using a convection technology with a 5-cm active tip placed at the nucleo-annular junction.⁸⁸ In an intradiscal electrothermal therapy (IDET) procedure, radiofrequency energy is converted into heat in a thermal resistive coil that is percutaneously placed into the disc with fluoroscopic guidance. Heat is delivered at a specific temperature for a specific length of time to thermocoagulate the nerves.⁸⁹ Intradiscal electrothermal therapy is based on the principles of destroying these nerves, thus leading to pain relief.⁸⁹ The procedure involves the introduction of a flexible electrode into the painful disc, with the aim of coagulating the posterior annulus.

Maurer et al.⁹⁰ in a prospective study concluded that durable clinical improvements can be realized after IDET in highly selected patients with mild disc degeneration, confirmatory imaging evidence of annular disruption, and concordant pain provocation by low-pressure discography. However, Freeman et al.⁹¹ in an RCT—IDET

compared with a sham treatment (placebo)—found that although the IDET procedure appeared safe with no permanent complications, no significant change in outcome measures in either group at 6 months was observed. Chou et al. concluded that there is insufficient (poor) evidence from randomized trials (conflicting trials, sparse and lower quality data, or no randomized trials) to reliably evaluate IDET and coblation nucleoplasty.⁷³ On the other hand, recently Helm et al. in a systemic review found the evidence to be fair for IDET, using current criteria for successful outcomes.⁹²

Radiofrequency Ablation

Radiofrequency ablation provides a well-controlled spherical lesion around an electrode tip. Although radiofrequency lesioning can provide temperature sufficient to thermocoagulate nervous tissue, it is limited by the distance it can transmit heat.⁸⁹

Sometimes classified as a variant of IDET, “percutaneous intradiscal radiofrequency therapy” (PIRFT) is a procedure involving the placement of an electrode of the catheter into the intervertebral disc and applying alternating radiofrequency current. Chou et al. in a review of RCTs and systemic review found fair evidence that PIRFT thermocoagulation is not effective.⁷³

Nucleoplasty

Nucleoplasty is a minimally invasive technique that was first approved by the US Food and Drug Administration in 2000.⁹³ It aims to achieve percutaneous disc decompression through patented coblation technology, which utilizes bipolar radiofrequency energy to ablate and remove disc material, with coagulation of the adjacent residual disc tissue. There is weak evidence that nucleoplasty is effective in the treatment of radicular leg pain due to contained disc herniation. However, there is no evidence available with regard to its role in managing discogenic, axial back pain.^{73,94} However, in our center, carefully selected 30 patients with discogenic axial low back pain responded well for pain relief for initial 2 years. Cuellar et al.⁹⁵ in an observational cohort study failed to detect any morphologic improvement of disc abnormalities by MRI evaluation in patients with persistent pain, who underwent nucleoplasty. Thirty-two percent showed progressive degeneration in <1 year after nucleoplasty, a rate greater than expected by natural progression during the interval of examination.

DiscFx

DiscFx (Elliquence, LLC) system uses manual debulking of the disc, annular modulation, and nucleus ablation while keeping the procedure minimally invasive. It has four components: discography, manual discectomy, nucleus ablation, and annulus modulation. The hypothesis for the mechanism of this system is that high, specific ablation rate and targeted modulation of the annulus leads to a significant shrinkage by a minimum temperature distribution. Modulation of the dorsal annulus by the trigger flex probe results in shrinkage of the collagen, cauterization of inflamed structures, shrinkage of the annulus by 30%, and widening of the epidural space by 10%, thus resulting in improvement of blood circulation and venous congestion in the epidural space. The steerable delivery system permits targeted application in the region of the pathology. In addition this reduces the intradiscal pressure as it removes approximately 0.8 g of material out of the disc. Annulus modulation may also cause reduction in pain generated by the annular nerve fibers in degenerative disc disease. Manual removal of the disc material by a disc rongeur allows adequate nerve root decompression.

CONCLUSION

The interventional modalities discussed above for diagnostic and therapeutic procedures are more important and established ones out of an exhaustive list of procedures. These procedures are evolving and increasing numbers; hence, readers have to assess the procedures they want to apply in their practice very carefully.

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Surgical Considerations in the Obese Patient

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Snapshot

- » Obesity and the Spine
- » Obesity and Outcomes of Spine Surgery
- » Complications and Surgical Comorbidities in the Obese Patients
- » Practical Tips

INTRODUCTION

Since the end of the 20th century, obesity has been identified as a global epidemic by the World Health Organization (WHO).¹ Recent estimates indicate that >1 billion people are overweight today and that >300 million are considered to be obese.² There is a general consensus about the definition of obesity: obesity is defined as a >20% greater body weight as compared with normal values, whereas morbid obesity is defined if the body mass index (BMI) exceeds 40 kg/m².^{3,4}

There is a steep rise in obesity in the western industrialized countries. For example, in the United States, the prevalence of obesity (BMI >30 kg/m²) increased from 14.5% in 1980 to 22.5% in 1994.⁵ In 2004, the statistics of the Centers for Disease Control showed that 67% of the US population was overweight and 32% obese.^{4,6} In 2005, Arterburn et al.⁷ reported that the US healthcare expenditures associated with morbid obesity were >111 billion US dollar in the year 2000.

The even more alarming finding is that these trends are not only seen in adults but also in children and adolescents.^{4,8,9} Similar observations have been made in European countries.^{8,10}

Overweight in children is associated with various musculoskeletal disorders, such as adolescent idiopathic scoliosis (AIS),^{11,12} slipped capital femoral epiphysis,^{13,14} axis disturbances in the lower extremity, or other growths disorders.¹⁵⁻¹⁷

Latest estimates of the WHO report 1.6 billion of people >15 years of age were overweight and at least 400 million of those were obese.¹⁸

In adults, the association between overweight and comorbidities, such as diabetes mellitus, hypertension, obstructive sleep apnea, cardiovascular disease, and increased mortality rates, has been described extensively.¹⁹⁻²¹ The combination of these medical disorders has been described as “metabolic syndrome.”²²⁻²⁶

OBESITY AND THE SPINE

In 1987, Heliövaara²⁷ for the first time identified an increased BMI as being an independent risk factor for herniated lumbar disc in men.

Two years later, Deyo and Bass²⁸ published the first survey, which analyzed the association between lifestyle and low back pain.²⁸ In a population of >27,000, they could show that smoking and obesity are independent risk factors for the development of low back pain. The most obese 20% of the subjects under investigation had a 1.7 times higher risk than the lowest 20% for developing low back pain. Even after controlling for age, gender, education level, exercise level, and employment status, obesity and smoking remained independent risk factors in a logistic regression analysis.

A meta-analysis of 56 articles from 65 epidemiologic studies about the association of body weight and low back pain published later could identify body weight of being only a weak risk factor for low back pain.²⁹

Other studies have shown a strong association between obesity and hospitalization for intervertebral disc disorders,³⁰ hospitalization for lumbar disc herniations,²⁷ radicular pain and neurologic signs,³¹ as well as severe lumbar disc herniation requiring surgery.³²

A population-based cross-sectional study among 63,968 adults performed in Norway ("The HUNT Study") indicated that obesity is associated with a high prevalence of low back pain.³³ A follow-up of this community-based study could also show that high levels of BMI may predispose to chronic low back pain 11 years later both in individuals with or without low back pain at baseline.³⁴

In a recently published smaller population, increased fat mass in the body composition of the study population was identified as being a risk factor for high levels of back pain intensity and disability.³⁵

There also seems to be a significant correlation between general and disease-specific functional health status and BMI. In the United States, a consortium of 26 spine centers (The National Spine Network) investigated 15,974 patients at their first visit. A total of 10,242 patients (64%) were obese [grade 1 (BMI: 25–29.9 kg/m²), $n = 5,732$; grade 2 (BMI: 30–39.9 kg/m²), $n = 3,836$; grade 3 (BMI > 40 kg/m²), $n = 561$]. The physical component summary scores of the Short Form (SF)-36 as well as the Oswestry Disability Index (ODI) were recorded. The general and disease-specific functional status was significantly worse in patients with a higher BMI.³¹ These patients also had higher pain scores and more comorbidities as compared to normally weighed patients. The spine patients who were morbidly obese (BMI > 40 kg/m²) had worse physical functioning as compared to patients with most other disease conditions.^{31,36–43}

In summary, there is strong evidence from the scientific literature that an increased BMI has a negative impact on the functional status of spine patients. Obesity may predispose for chronic low back pain and has a potentially negative influence on various (mainly degenerative) lumbar spine pathologies.

OBESITY AND OUTCOMES OF SPINE SURGERY

Surgery for Adolescent Idiopathic Scoliosis (AIS)

There is only scarce data on whether obesity acts as an independent determinant for the outcome of spinal surgery. In 2008, Upasani et al.¹⁸ investigated the influence

of obesity on the surgical outcome in AIS. In a prospective, uncontrolled study on 241 patients, who were operated for AIS, the preoperative rate of obese patients was 19.9% (48/241).

The authors could not identify a significant influence of overweight neither on clinical outcomes (self-image, function, and patient satisfaction) nor on perioperative morbidity or mortality. There was also no effect of obesity on the ability to achieve or maintain correction of the deformity. However, in the group of overweighted patients ($n = 48$), the degree of obesity was quite moderate with an average BMI of 26 kg/m² (range: 20.9–37.0 kg/m²). This might be an explanation for the lack of significant differences among the two groups.

Conclusion

In the rather young patient population suffering from idiopathic scoliosis, the prevalence of obese patients is low. No significant influence on perioperative morbidity, degree and maintenance of correction, as well as on clinical outcomes, could be identified hitherto.

Surgery for Degenerative Spinal Stenosis

In a series of 2,633 patient [46% overweighted (BMI: 25–29.9 kg/m²); 23% obese (BMI > 30 kg/m²)], who had surgery for lumbar spinal stenosis, clinical outcomes as measured with Euro-QoL Group Index and ODI were analyzed from the Swedish Spine Registry.⁴⁴ Although all patients showed a good improvement from baseline, the outcomes in obese patients after 2 years showed a significantly increased use of analgesics, more leg and back pain, an inferior quality of life, and a higher rate of dissatisfaction.⁴⁴

Two clinical studies recently described the influence of obesity on the outcomes of patients surgically treated for degenerative lumbar spinal stenosis. Within the Spine Patient Outcome Research Trial a total of 373 normally weighed patients (BMI < 30 kg/m²) versus 261 obese patients (BMI > 30 kg/m²) with degenerative lumbar spinal stenosis were identified.⁴⁵ Treatment effects (operative and nonoperative) were analyzed at a 4-year follow-up in both groups. Primary outcome measures were SF-36 bodily pain and SF-36 physical function, as well as ODI. Regardless of BMI, patients who had been operated had better outcomes at all time points as compared to those treated without operation. There was no influence of the BMI, neither on peri- or postoperative morbidity nor on complications, mortality, or primary outcome measures.

Another group of 376 non-obese versus 225 obese patients with a combination of spinal stenosis and degenerative spondylolisthesis (DS) was analyzed within the same trial. In this group as well, surgical outcome was significantly better as compared to nonoperative treatment. However, at 4-year follow-up, patients who had undergone surgery for DS had less improvement from baseline primary outcome measures. There was a significantly increased wound infection rate in the obese patients as well as two times higher reoperation rate within a 4-year follow-up.⁴⁵

Summary

There seems to be no scientific evidence for inferior outcomes or increased perioperative morbidity in patients who undergo decompression alone for lumbar spinal stenosis. However, if decompression is combined with surgical stabilization/fusion, obese patients seem to have less improvement at 4-year follow-up as well as a higher rate of wound infection and reoperations.

Obesity and Lumbar Fusion

Instrumented surgical fusion of motion segments of the lumbar spine is exposed to significantly higher biomechanical loads in obese as compared to normal weighed patients. This might influence the “healing process” of fusion, the speed of material fatigue (e.g. pedicle screws), as well as the postoperative outcome. In a retrospective analysis of 270 patients treated at a single center, Djurasovic et al.⁶ analyzed the influence of obesity on clinical outcome after lumbar fusion.

They looked at the clinical results of patients who had undergone lumbar fusion for various pathologies, such as DS, “instability” (not further specified), spinal stenosis, scoliosis (not further specified), disc pathology, nonunion, and others. They classified obese patients ($n = 109$) with having a BMI of $> 30 \text{ kg/m}^2$ versus nonobese ($n = 161$) with a BMI of $< 30 \text{ kg/m}^2$. Outcomes were measured using the ODI, SF-36 questionnaires, and Visual Analog Scale (VAS) leg and back pain pre- and 2 years postoperative.

There was a trend toward better outcomes of non-obese versus obese patients; however, the mean improvements in both groups did not show a statistically significant difference.

The overall complication rate however was significantly different with a total of 28.4% complications in the obese group versus 17.4% in the non-obese group.

The higher complication rate was mainly attributed to a higher rate of wound infections and wound healing disturbances.

Another recently published analysis of lumbar spine fusion patients focused on differences between obese (BMI $> 30 \text{ kg/m}^2$) and morbidly obese (BMI $> 35 \text{ kg/m}^2$ + significant comorbidities), the latter being considered as a high-risk group.⁴⁶ A total of 63 patients (32 obese; 31 morbidly obese) were analyzed retrospectively after having undergone a lumbar fusion operation. Fusion had been performed mainly for degenerative pathologies. The American Association of Anesthesiologists (ASA) scores were higher in the morbidly obese group indicating a generally higher surgical risk. The authors could not identify a significant difference in surgical time, blood loss, hospital stay, or the outcomes between the two groups as referred to VAS and ODI scores. However, overall complication rates of 45% (morbidly obese) and 44% (obese) were high. Interestingly, although there was a significant improvement of symptoms in both groups postoperatively, no weight loss was achieved at an average follow-up of 20.4 months.

A very recent paper published in 2012 describes the epidemiology and outcomes of lumbar fusion surgery as referred to the presence of a metabolic syndrome.²⁶ Although there are various definitions of metabolic syndrome, there seems to be a consensus that the coincidence of obesity, diabetes, hypertension, and dyslipidemia should be considered as metabolic syndrome.^{24,25} The analysis was carried out for the years 2000–2008 in a total of 238,296 patients who were identified through the National Inpatient Sample (NIS) in the United States of having been admitted to a hospital for posterior lumbar spine fusion. Interestingly, the increase of metabolic syndrome over this 8 years period was more than threefold with an average prevalence of 9% in the 2008 patient population. The outcome analysis showed significant differences between patients with or without metabolic syndrome. Length of hospital stay was longer, hospital charges were higher, nonroutine discharges were more frequent, and here was a significantly higher rate of life-threatening complications in patients with metabolic syndrome.²⁶

A retrospective cross-sectional study of spinal fusions in California from 2003 to 2007 was published by Kalanithi et al.⁴⁷ in 2012. They analyzed healthcare costs and complications in 84,607 hospital admissions. The data were taken from the Health Care Cost and Utilization Project's California State Inpatient databases. The analysis focused on patients who had undergone one of four types of spinal

fusion: anterior cervical fusion, anterior lumbar fusion, posterior cervical fusion, and posterior lumbar fusion. In-hospital complication rates were 97% higher in morbidly obese patients undergoing one of these procedures as compared to normally weighed patients (13.6% vs 6.9%). Mortality in the obese patients was higher (0.41 vs 0.13; $p < 0.01$). Average hospital costs were higher ($p < 0.0001$), as well as length of stay ($p < 0.0001$). Morbid obesity turned out to be the most significant predictor for complications in anterior cervical and posterior lumbar fusion.

Summary

Although the overall outcomes of obese patients undergoing lumbar spine fusions for various (mainly degenerative) pathologies do not seem to differ from nonobese patients, there is increasing evidence that perioperative morbidity and complication rates including life-threatening complications seem to be significantly higher in obese patients or in patients suffering from metabolic syndrome. This seems to be associated with increased overall costs.

COMPLICATIONS AND SURGICAL COMORBIDITIES IN THE OBESE PATIENTS

The analysis of currently available data shows that the complication rates of different types of spinal surgery in obese patients ranges from as low as 12.5% in young patients suffering from idiopathic scoliosis without significant comorbidities¹⁸ to up to 74.1% in the typical patient population undergoing spinal surgery for degenerative spine disorders.^{6,10,26,45-48} Whereas technical and intraoperative aspects seem to play a minor role, it can be assumed that the comorbidities are the significant drivers of these complication rates. Moreover, surgical site infections (SSIs) and wound healing disturbances ascribe for the majority of postoperative complications in obese patients.^{6,10,26,45,48} In a recently published meta-analysis on SSI after spinal surgery, only obesity, diabetes mellitus, and previous SSI could be identified as being significant risk factors.⁴⁹ The distribution of body fat seems to be more important for the development of SSI than the BMI per se. Mehta et al.⁵⁰ recently could find that, besides the number of operated levels, the skin-to-lamina-distance and the thickness of subcutaneous fat were significant risk factors for SSI, whereas BMI itself was not.⁵⁰

In any case, SSI seems to be one of the most important complications to be avoided since it is one of the top

three reasons for unplanned readmission to hospitals after spinal surgery⁵¹ and leads to a reoperation in the majority of the cases.

In most of the published papers, the prevalence of preoperative comorbidities shows a wide range between 0.9% and 100%; however, they always contribute significantly to the rates of peri- and postoperative complications, length of hospital stay, and costs.^{26,45,46}

PRACTICAL TIPS

Expectation Management

From the author's personal experience and from the available data in the scientific literature, it seems to be important to achieve a shared decision on surgery together with the patient. The majority of obese patients undergo elective surgical procedures for degenerative spine pathologies. This means that if we consider the current scientific data in complications and outcomes, an individual risk-benefit analysis is necessary for each individual case. The dialogue with the patient to achieve an informed consent must address unrealistic expectations on the patient's side. And last but not least, the influence of obesity on further degeneration of the patient's spine should be discussed.

Morbidly obese patients should not generally being denied spinal surgery; however, compliance needs to be obtained. The increased risk potential due to obesity should be openly discussed. In cases with no time pressure, patients should be motivated to first loose weight before an operation is performed. In morbidly obese patients, the author strongly recommends his patients to consult a bariatric surgeon preferably before the planned operation.

The patient must be informed specifically about all additional surgical risks, which are associated with his or her overweight. If from a surgeon's and anesthesiologist's point of view the risks overrate the expected benefits, surgery should be avoided. Do not forget that most patients do not loose weight after surgery, although they often pretend that the loss of mobility is responsible for their weight increase.⁴⁶

This might influence your surgical decision especially when spinal fusion is considered.

Technical Aspects

Patient positioning can be difficult (Fig. 8.1) to avoid pressure sores; head, arms, and knees have to be carefully protected (Figs. 8.2 to 8.4). Occasionally, positioning needs to be modified. Most obese patients have heavy heads, so



Fig. 8.1: Difficult knee-chest positioning for lumbar decompression in an obese patient.



Fig. 8.2: Risk of pressure lesion of ulnar or median nerve.



Fig. 8.3: The knees need to be supported to avoid slipping from the operating room (OR) table (Attention: Avoid pressure on the peroneal nerve).



Fig. 8.4: The head needs to be positioned without pressure on eyes, nose, and mouth.

eye protection plays an important role to avoid postoperative amaurosis or lesions around the eye (Fig. 8.5).⁵²

There are first reports, which describe potential advantages of minimally invasive approaches to the spine in obese patients.^{26,53,54} There is currently not enough scientific evidence in the literature to support the argument that complications rates and/or outcomes can be improved with the use of less invasive approaches; however, the advantages of minimally invasive spine surgery, such as less tissue trauma, small approaches, less blood loss, shorter immobilization, and shorter hospitalization, suggest a potential and special benefit of the use of these techniques in obese patients.

Careful tissue handling, avoidance of retractor pressure on skin and muscles, careful hemostasis, and all measures, which potentially avoid SSI, are important. This includes repeated wound irrigations intraoperatively, shortening of operating room (OR) times, application of local antibiotics, or prolonged infection prophylaxis perioperatively.

CONCLUSION

The beneficial effect of bariatric surgery on the spine has been analyzed recently in an interesting prospective study.⁵⁵ In a prospective series of morbidly obese patients (BMI >35 kg/m²) with low back pain, bariatric surgery was performed (laparoscopic gastric banding, sleeve



Fig. 8.5: Postoperative pressure sore around the eye after prone positioning.

gastrectomy, laparoscopic Roux-en Y gastric bypass, and duodenal switch). Average reduction of BMI was from 42.8 to 29.7 kg/m² at 1-year follow-up. Low back pain and radicular pain significantly decreased ($p < 0.001$). Moore-head-Ardelt life quality score improved significantly ($p < 0.001$). The most interesting finding however was that there was a significant increase in L4-5 disc height ($p < 0.001$) as measured pre- and 1-year postoperative with computed tomography scan.

This is the first paper, which describes a significant influence of weight loss on disc height, thus indicating a beneficial effect on the degenerating disc.

In summary, obese patients undergoing spine surgery need special attention. Their outcomes seem to be comparable with non-obese patients, however, associated with a significantly higher risk of experiencing complications (mainly wound infections and general complications). If spine surgery can be postponed, bariatric surgery is recommended before spine surgery.

If surgery cannot be postponed in morbidly obese patients, bariatric surgery should be recommended after spine surgery.⁵⁶⁻⁵⁸

KEY POINTS

- Obesity is associated with other comorbidities and increases the risk potential for spinal surgery.
- Wound infections and general complications are higher in obese patients as compared to normally weighted patients.

- Obesity predisposes for experiencing low back pain and has a negative influence on the natural course of degenerative spine pathologies.
- Morbidly obese patients for whom spinal surgery is planned should be seen by a specialists in bariatric surgery before spine surgery as part of the routine preoperative workup.
- The indication for surgery should be restrictive in obese patients, and, if surgery cannot be avoided, a strict expectation management before the operation is mandatory.

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Surgical Considerations in the Geriatric Patient

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Snapshot

- » Physiologic and Pharmacologic Effects of Aging
- » Preoperative Assessment
- » Medications
- » Assessment of the Home and Preoperative Teaching
- » Nursing Care in the Operating Room
- » Postoperative Nursing Care in Postanesthesia Care Unit
- » Postoperative Care on the General Nursing Unit
- » Perioperative Side Effects and Complications

INTRODUCTION

The pathophysiology, pathoanatomy, and pathomechanics of the spine in the aging patient form the basis for the discussion of the spinal disorders seen in the elderly. Spondylosis, metabolic bone disease (specifically, osteoporosis), and tumor are seen much more commonly in the geriatric population. Spondylosis is a degenerative local process specifically affecting the spine, whereas osteoporosis and other metabolic bone diseases are systemic processes that preferentially affect the spine because it contains the largest quantity of metabolically active trabecular bone. Malignant spinal neoplasms may be categorized as either primary or secondary. Also, they may be either local or metastatic. The treatment of the elderly patient with a spinal disorder is challenging and involves numerous issues not relevant in younger patients (Table 9.1).

PHYSIOLOGIC AND PHARMACOLOGIC EFFECTS OF AGING

Basal Metabolic Rate and Temperature Regulation

The basal metabolic rate (BMR) declines 1–2% per decade from the age of 20–80 years.¹ Aging combined with a decreased level of physical activity contributes to this decrease in BMR. Shivering is less common in older patients

Table 9.1: Spinal disorders in the elderly.

<i>Disorders</i>	<i>Specific conditions</i>
Degenerative	Lumbar disc disease Back pain Radiculopathy Neurogenic claudication Cervical disc disease Neck pain Radiculopathy Myelopathy
Deformity	Degenerative spondylolisthesis Degenerative scoliosis
Trauma	Compression fractures Central cord syndrome
Tumor	Metastatic disease Primary bone tumor
Infection	Pyogenic vertebral osteomyelitis Granulomatous vertebral osteomyelitis
Inflammatory	Rheumatoid arthritis Atlantoaxial instability Basilar invagination Subaxial instability Ankylosing spondylitis

because a lower core temperature must be reached to trigger a response,² placing the elderly at greater risk of perioperative hypothermia.

Cardiovascular Function

Advancing age is associated with loss of arterial elasticity and reduced arterial compliance as elastin production declines and collagen is damaged over time, leading to an overall “stiffening” of the heart and vascular system.³ The progressive reduction in nitric oxide production with aging also contributes to vascular stiffening.⁴ As the aging heart pumps against an increased afterload, the left ventricular wall thickens, leading to ventricular hypertrophy.⁵ Although these age-related changes in cardiac function preserve systolic function, the decrease in left ventricular compliance impairs early diastolic filling, making the aging heart dependent on late diastolic filling.⁶ Because late diastolic filling is a function of atrial function, hemodynamic instability can result from the presence of supraventricular arrhythmias.⁷ Impairment in the ventricular relaxation phase, termed *diastolic dysfunction*, also predisposes the elderly patient to fluid overload and “flash” pulmonary edema.⁸

Autonomic Nervous System Function

Autonomic nervous system (ANS) function progresses from parasympathetic predominance at birth to gradually increasing sympathetic activity in early adulthood. Sympathetic activity predominates in later life as parasympathetic activity progressively declines. A concomitant decrease in β -adrenoreceptor responsiveness renders the elderly patient's ANS less capable of responding to stressful stimuli.⁵ The baroreflex likewise suffers from the age-related decrease in vagal activity, resulting in a reduced capacity to maintain a stable arterial blood pressure in response to acute physiologic changes during the perioperative period.⁹ The combination of ANS changes and structural changes in the cardiovascular system can increase blood pressure variability.⁷ The clinical consequences of autonomic aging include increased blood pressure lability, reduced responsiveness to inotropic and chronotropic drugs, and an increased dependence on preload to maintain cardiac output.

Pulmonary Changes

After the age of 50 years, lung compliance decreases secondary to loss of parenchymal elasticity, loss of chest wall compliance due to calcification of the costochondral joints, and decrease in alveolar surface area.¹⁰ These changes result in a decrease in vital capacity, expiratory flow, and diffusion capacity, and an increase in residual volume, closing capacity, dead space, and ventilation-perfusion

heterogeneity.¹⁰ Clinically, elderly patients experience gas exchange abnormalities that require progressively increasing inspired oxygen concentrations.¹¹ Older patients also have impaired respiratory responses to hypoxia and hypercapnia and an increased sensitivity to the respiratory-depressant effects of opioid analgesics and benzodiazepines.¹⁰ Advanced age is an important predictor of postoperative pulmonary complications, including aspiration, pulmonary edema, atelectasis, and pneumonia.¹²

Renal and Hepatic Effects

The kidneys lose approximately 10% of parenchymal thickness per decade of life,¹³ accompanied by a 10% decline in renal blood flow per decade, contributing to a 30–50% decrease in creatinine clearance between the age of 20 and 90 years.¹⁴ Despite this decline in renal function, serum creatinine levels remain in the normal range because the production of creatinine decreases as a result of the loss of muscle mass, which occurs at a rate similar to the decline in glomerular filtration rate. Liver mass also decreases by 20–40% during the typical human lifespan, with a concomitant decline in hepatic bloodflow.¹⁵ Impaired hepatic and renal function in elderly patients affects the metabolism and excretion of many different anesthetic, analgesic, and muscle-relaxant drugs.

Cerebral Effects

Cerebral atrophy increases and cerebral perfusion decreases after the age of 60 years, but there is marked heterogeneity in the magnitude of these changes.¹⁶ On average, there is a 15% decrease in white matter by the age of 90 years,¹⁷ which may predispose the elderly to postoperative cognitive disorders^{18–20} and increase their sensitivity to the central depressant effects of anesthetic medications. Aging results in an overall loss of neurons in both the cerebral cortex and the spinal cord and slows conduction velocity in peripheral nerves, resulting in an increased sensitivity to the local anesthetics used in neuraxial and peripheral nerve blocks.²¹ However, a cause-and-effect relationship has not been firmly established between neurodegenerative disorders and anesthesia in the elderly.²²

Effects of Aging on Pharmacologic Effects of Anesthetic Drugs

As individuals age, there is a progressive loss of skeletal muscle mass and total body water as muscle is replaced

with adipose tissue, especially in women. An increase in adipose tissue leads to an expansion of the “lipid (deep) reservoir” for centrally active anesthetic drugs [e.g. benzodiazepines, volatile agents, opioid analgesics, and sedative-hypnotics (IV anesthetics)], contributing to prolonged elimination half-life values and an increased duration of action of these drugs in the elderly.²³ In addition, the reduction in total body water decreases the central volume of distribution for water-soluble drugs, resulting in higher average and peak plasma drug concentrations and an enhanced peak (maximal) effect.¹⁴ Older patients with poor nutrition can have a 20% or more decrease in albumin levels. Because many anesthetic drugs are highly bound to albumin (e.g. propofol and diazepam), even modest decreases in albumin levels can increase free-drug concentrations, contributing to increased sensitivity to these drugs in the elderly.

Although oral drug absorption from the gastrointestinal tract is often delayed in the elderly, these changes are of minimal importance in the perioperative setting because the majority of anesthetic and analgesic medications are administered intravenously. Age-related pharmacokinetic changes in drug distribution, metabolism, and elimination have a significant impact on drug dosing in geriatric patients.^{21,23,24} The mechanisms responsible for the pharmacodynamic changes associated with aging are less well understood. However, the aging of the central nervous system results in neuronal loss and a decline in cognitive reserve, contributing to the enhanced sensitivity of the elderly to centrally active anesthetic drugs. As a result of these age-related changes, the central nervous system depressant effects of anesthetic drugs (e.g. sedation, hypnosis, and cardiorespiratory depression) occur at lower blood and effect-site concentrations in older patients.²² The old adage to “start low and go slow” applies when administering potent anesthetic and analgesic drugs to elderly patients in the ambulatory setting.

Drug Interactions in the Perioperative Period

Polypharmacy, the term used to describe the use of multiple chronic medications, is common among elderly patients undergoing ambulatory surgery procedures. It is estimated that 40% of geriatric patients take five or more different drugs per week, and 12–19% use 10 or more drugs in a week.²⁵ An expert panel found that polypharmacy (defined as five or more chronic medications) was the only patient characteristic associated with adverse drug

reactions in patients >65 years.²⁶ Combinations of analgesic medications (e.g. opioids, local anesthetics, and anti-inflammatory drugs) can produce enhanced postoperative analgesia as part of a multimodal regimen, but their interactions may contribute to delayed wound healing in the elderly.^{27,28} Anesthesia providers should be aware of all prescription, “over-the-counter,” and herbal medications taken by elderly outpatients to minimize adverse events from drug interactions in this high-risk surgical population.

PREOPERATIVE ASSESSMENT

Indication and Goals of Surgery in the Geriatric Patient

The basic indication for surgery in the elderly patient is failure of conservative treatment after a reasonable period of time. For example, pain management is the primary consideration and goal of elective foot surgery in the geriatric patient.²⁹ Severe foot pain can result in an active alert older patient becoming nonfunctional, dependent, and severely depressed.

Functional restoration enabling the individual to resume former activities of daily living (i.e. ambulation) is the second goal of surgery. An elderly patient may not be able to ambulate as a result of a particularly severe hallux valgus deformity, permitting the patient to walk again and resume activities of daily living.

Limb salvage is a critical primary goal of surgery in the older debilitated patient. Quality of life is an important consideration. The number of lower extremity amputations for diabetes and malignancies has been reduced markedly to offer the individual a higher quality remainder of life.

Review of Systems

Physiologic changes occur with normal aging even in completely healthy individuals. The major changes in the cardiovascular system seen with aging are related to stiffening and decreased distensibility of the systemic arteries and the cardiac wall. The cardiovascular system in the elderly patient usually responds less well to stress. General physiologic aging changes, such as decreased cardiac efficiency, arteriosclerotic vessel lumen narrowing with decreased tissue perfusion, and pathologic conditions, such as ischemic heart disease, hypertension, cardiac arrhythmias, and congestive heart failure, diminish the geriatric patient’s ability to respond to the stress of surgery.²⁹

Respiratory system function declines in the geriatric individual as a result of aging. With aging, the breakdown of elastin and cross-linking of collagen impair the elastic recoil of the lung. The chest wall becomes less compliant. Pulmonary circulation is reduced as a result of proliferation and fibrosis of the intimal and medial layers of the pulmonary arteries.

Renal function declines in aging with a gradual loss of renal mass. There are minimal losses of functional changes in the liver because of the presence of substantial hepatic reserve. The immune system is also diminished in the elderly. There is a decrease in cell-mediated and humoral immunities. The system that undergoes the most changes in the elderly is possibly the musculoskeletal system. The rate of bone loss following menopause may temporarily approach 3% a year in some women. Bones typically become less stiff, less strong, and more brittle with aging.

Osteoporosis occurs more frequently in the elderly. Calcium supplement perioperatively is helpful in speeding bony healing and in slowing the osteoporotic process. The geriatric patient with osteoporosis should not have base wedge surgery and postoperatively should not be casted for a long period of time.³⁰ The procedure for a patient with any degree of osteoporosis must allow for early postoperative ambulation. If a cast must be used, it should be bivalved for easy removal, or a lightweight prefabricated walking brace might be more appropriate.

Muscles become less powerful with reduction in the fast-twitch type II muscle fibers and a reduction in the number of motor units. Aging increases the amount of connective tissue, which results in decreased range of motion and increased muscle stiffness. The density of bone decreases, especially in postmenopausal women. Osteoporosis is common, also reducing the potential for postoperative healing.

Osteoarthritis is common in > 70 years. Bone, cartilage, fascia, tendons, ligaments, and joint capsules may all be severely weakened.²⁹ Osteoarthritis is most common in the elderly hip and knee and will impact postoperative healing of foot surgery.

Estimating General Risks of the Surgery and Reducing Them

The American Society of Anesthesiologists (ASA) criteria remain the best tool for estimating the overall risk of surgery. Patients are divided into five clinical categories that predict mortality in elective and emergency surgery. Class 1

Table 9.2: American Society of Anesthesiologists physical status scale and risk of surgery.

Class	Physical status
I	Normal healthy individual
II	Mild systemic disease
III	Severe nonincapacitating systemic disease
IV	Severe incapacitating systemic disease with a constant threat of life
V	Moribund patient who is not expected to survive 24 hours with or without operation
VI	Added to any class patient undergoing emergency surgery

is the normal healthy individual. The ASA scale adjusts for age by not permitting an elderly person to receive a class 1 designation. Patients >80 years by definition are at least ASA class 2. Patients with severe systems disturbances that were not life threatening (class 3) have 4% mortality rate. Patients with life-threatening physiologic derangement are class 4 and have 25% mortality rate in surgery. Patients who will not survive for 24 hours without the operation are class 5. Emergency operations are classified as “E” and double the risk.³¹ If the patient is classified in any category other than class 1 or 2, hospitalization is often advisable for even minor procedures, such as removing nails or warts, unless an anesthesiologist is available to monitor the patient in the office³⁰ (Table 9.2).

Because podiatric surgery is generally elective, the patient’s overall health should determine whether and when the surgery should be performed. Because geriatric patient with a high rate of increased concomitant diseases and suboptimal biological factors is at increased risk for surgery, the surgeon and anesthesiologist should be taken all measures to reduce the risk as much as possible. These measures include strict selection of indications for operative treatment. Because the great majority of podiatric surgery is elective, the surgery should be absolutely necessary to alleviate pain and improve function. The patient who is nonambulatory or whose ambulation is minimal should be ruled out as a candidate for elective surgery.³²

The patient’s expected lifespan must be considered. The patient must have a reasonable expectation of living long enough to benefit from the surgery. Although a 75-year-old woman can expect to live to the age of 87 years, approximately seven of her remaining years are likely to be marked by at least partial loss of functional independence.³³

There must be full preoperative preparation for the surgery, which includes clinical and psychological preparation. The most appropriate and least aggressive surgical procedure should be selected. The actual time it takes to perform the surgery is also a consideration. Lengthy procedures may expose the patient to infection, shock, atelectasis, and vascular problems. If the procedure must be lengthy, it might be best to stage the procedure rather than doing the entire procedure at once. Digital or nail surgery can be successfully performed in an office setting, but major podiatric surgery should be performed in a hospital.³² The anesthesia should be appropriate and localized if possible. A tourniquet should be used to prevent precipitating ischemic gangrene and venous damage causing thrombophlebitis. Paradoxically, not using a tourniquet may increase blood loss and even a small blood loss in the older patient can reduce output significantly. Drains should also be avoided if possible.³² The postoperative period should emphasize mobility, and the patient should spend as brief a time in bed as possible.

Choice of Anesthetic Technique

In the elderly population, it is good to minimize the length of stay in the hospital, with a quick return to their normal surroundings. For this reason, optimal choice of anesthetic technique can play a very important role in achieving this goal. For example, selection of a regional (spinal or epidural) anesthetic technique may be more desirable than general anesthesia in the elderly, where potential complications (e.g. aspiration or postanesthesia delirium) could prolong hospital stay. Good communication between the surgeon and the anesthesiologist is essential in this situation.

Local Anesthesia

Many minor urologic procedures can be done either in the office or in an outpatient setting using local anesthetics. The advantages of such a choice of anesthesia in the elderly patient include lower cost, ease of administration, and a quick return to their normal environment. Although the use of local anesthetics often is considered trivial, one must be aware of the potential complications or toxic reactions to local anesthetics if used improperly. Often the urologist administers not only the local anesthetic but also many intravenous sedatives (e.g. benzodiazepines) to supplement the local anesthesia. Knowledge of the potential adverse reactions to these sedatives and their treatment is very important, especially in the elderly population where

the response to many sedatives often is exaggerated and prolonged. Proper monitoring in this setting, including blood pressure, respiratory rate, and pulse oximetry, by qualified personnel is essential. When scheduling the patient for an office procedure that may require supplemental sedation, it is important that they are informed of the need to have someone who can drive them home after the procedure.

Regional Anesthesia

Use of regional anesthetic techniques in urologic practice, especially spinal and more recently epidural, is very popular because most procedures take place in the lower abdomen or pelvis. The advantage of this is that the pulmonary ventilation, myocardial function, and cerebral blood flow all remain unaffected.³⁴ Another important advantage of the regional technique is that the patient is allowed to remain awake during the procedure.^{34,35} This allows the anesthetist to constantly assess the patient's mental status, especially in a patient with preoperative cognitive impairment.³⁵ The patient can also make the surgeon or anesthetist aware of any potential complications (e.g. chest pain and diaphragmatic irritation) that may occur during the procedure.³⁴

Depending on the type and length of procedure performed, a single shot of either a short-acting local anesthetic (e.g. lidocaine) or longer acting agent (e.g. bupivacaine) may be selected. The anesthetist must be aware of the age-associated decrease in the quantity and change in the configuration of myelinated fibers in the dorsal and ventral roots of the spinal cord, thus requiring a reduction in the amount of local anesthetic given.³⁶ For many major urologic procedures in the elderly patient these techniques can be used for longer periods of time (i.e. continuous spinal or epidural). Even if the entire surgical procedure cannot be performed with the patient awake, the use of continuous regional anesthetic catheters allows for a reduction in the amount of general anesthetic required, which is of great importance in the elderly patient. Another advantage of the epidural catheter is that it can be used in the postoperative period with either a constant infusion or by patient-controlled analgesia (PCA), thus reducing the amount of postoperative pain and allowing for early ambulation to help prevent deep venous thrombosis.

Recently, a randomized study was undertaken by Shir et al.³⁷ on the effect of general anesthesia versus epidural anesthesia in postoperative pain and analgesic requirements in patients undergoing radical prostatectomy.

Patients were assigned randomly to receive epidural anesthesia, combined epidural and general anesthesia, or general anesthesia only. Results revealed that intraoperatively, epidural patients received significantly more epidural bupivacaine than combined epidural and general anesthesia patients. Recovery room median residual sensory level in epidural patients was significantly higher than in combined patients. The PCA demand was greater in the general anesthesia and combined groups when compared with the epidural group in the postoperative period, but there was no difference between the combined and general groups. There were no significant differences in postoperative mean pain scores in the first 5 days after surgery in the three anesthetic groups. They concluded that epidural local anesthetics were associated with decreased postoperative analgesic demands.

General Anesthesia

For many reasons, local or regional anesthesia is preferred in the elderly population; however, for many patients these techniques may not be practical or possible and a general anesthetic is required. The major disadvantage in this situation is that the patient is asleep, and the anesthesiologist must rely on various monitors [e.g. continuous electrocardiography (ECG), pulse oximetry, and blood pressure monitoring] to be aware of the status of the patient. Limiting the use of general anesthesia in elderly patients minimizes the occurrence of postoperative mental changes, which have been known to last for months or years after administration of general anesthesia.³⁸ Introduction or maintenance of general anesthesia may be done by either intravenous or inhalational anesthetics or a combination of the two. This does allow for some flexibility in adjusting anesthetic agents to fit the specific needs of the patient with many comorbid conditions.

MEDICATIONS

Thorough assessment on consumed medications by an elderly should be done before the surgery. Aspirin, clopidogrel, nonsteroids, and other antiplatelet drugs increase the risk of perioperative bleeding and, if not necessary, should be discontinued for 7–10 days. Drugs with anticholinergic effects should also be discontinued, because they could increase the risk of perioperative delirium. The use of chronic benzodiazepine agents should be taken into account and should be tapered off to minimize the risk of withdrawal effect when the patient should fast during

perioperative period. When it is not essential to manage excessive fluid volume or symptoms of lung edema in patients with congestive heart failure, discontinuation of diuretic agents for 24–48 hours before the surgery should be considered. Patients consuming antiepileptic, cardiovascular, and antihypertensive agents usually have to take the drugs in the morning before the surgery using as little water as possible. An abrupt discontinuation of β -adrenergic inhibitors and clonidine is associated with significant cardiovascular complication. Oral hypoglycemic agents usually should not be taken the night before surgery to minimize the risk of perioperative hypoglycemia. Diabetic patients receiving intermediate-acting insulin therapy usually receive half their regular dosage in the morning before the surgery, and intravenous 5% dextrose is given. Plasma glucose level >250 mg/dL after the surgery could be managed with subcutaneous insulin, or if the patient is in unstable hemodynamic state (could cause altered absorption of subcutaneous insulin) short-acting insulin infusion is given. Adrenal suppression due to chronic use of steroid should be treated with steroid, usually 100 mg of hydrocortisone every 6 hours, starting from the night before the surgery and then the dose is reduced until it reaches maintenance dose in 3–5 days in relation to the postoperative condition.

ASSESSMENT OF THE HOME AND PREOPERATIVE TEACHING

When the patient presents for a presurgical clearance, an assessment of the home environment needs to be completed by the nurse. These are extremely important questions that should be answered and addressed preoperatively for the elderly patient. The case manager or social worker should be consulted as needed. Trying to solve family issues/concerns after surgery is always more difficult.

The elderly population requires extensive preoperative teaching. Patients and their support person should be told what information they need to bring for the day of surgery. Additional preoperative teaching includes a discussion of the patient's fasting status.

Other topics for discussion during the patient's preoperative teaching include the following:

- Discuss the importance of leaving all valuables at home, thus protecting the patient and the surgical facility from theft or loss.
- Ask the patient to wear loose, comfortable clothing. Elastic waist pants and slip-on shoes work the best when elderly patients have to get dressed postoperatively.

- Discuss with the patient which medications he or she should take prior to surgery and which medicines need to be withheld.
- Carefully review any skin preparation or bowel preparation with the patient and his or her significant other.
- Take the opportunity to teach the patient how to use the incentive spirometer if indicated. Coughing and deep breathing exercises should be taught with return demonstration, and patients should be shown how to splint the area of incision during deep breathing exercises.
- Discuss pain management with the elderly patient to help dismiss any misconceptions regarding pain control. Remember, many people in this generation still fear “getting addicted.”³⁹

■ NURSING CARE IN THE OPERATING ROOM

Fluid Status

The patient’s fluid status should be frequently assessed. Dehydration is a common problem for the geriatric surgical patient, especially those who come from a long-term care facility. Patient assessment should include observing vital signs, monitoring urine output, and assessing skin turgor. The patient’s fluid and electrolyte status needs to be monitored and well managed. Cleansing enemas and the use of diuretics can place the elderly at risk for dehydration.⁴⁰ Assess the patient’s mucous membranes and skin for signs of dehydration. It is helpful if elderly patients are scheduled for surgery early in the day, so they are not NPO for any longer than necessary. For surgeries late in the day, allow the patient to have a light breakfast when possible.

Positioning

In the operating room (OR), the elderly patient requires special attention. Positioning is a priority, and extra care needs to be taken to protect the spine and back. Many elderly patients are slender and their skin is fragile. They require extra padding over bony prominences.⁴⁰ Many elderly people have osteoarthritis.

Temperature Regulation

Another major problem for the elderly in the OR can be temperature regulation. Older patients are more susceptible to hypothermia due to loss of body fat.⁴⁰ Operating

rooms are kept cool and if surgery is prolonged, the patient may lose a significant amount of body heat. The use of warming blankets can help reduce the risk for hypothermia. Cover the patient’s head when possible to avoid the loss of body heat. In addition, cover their feet with paper slippers or 100% cotton socks. Inspect the patient’s feet prior to entering the OR for any signs of infections (i.e. in-grown toenails).

■ POSTOPERATIVE NURSING CARE IN POSTANESTHESIA CARE UNIT

Postoperative care of the geriatric patient in postanesthesia care unit (PACU) is a systematic process. Airway, breathing, and circulation (ABC) is the priority in phase I PACU. All patients arriving in the PACU should be assessed for the need for supplemental oxygen, especially those who received heavy sedation or general anesthesia.⁴¹ Respiratory effort and vital signs must be closely monitored. Knowing the preoperative oxygen saturation is extremely important in the PACU. Oxygen saturations of 93–95% may be normal values for the elderly patient, especially those with existing pulmonary disease.⁴² The patient’s level of consciousness and return of protective reflexes are evaluated continuously. Muscle strength is noted, especially if muscle relaxants were used in the OR. Geriatric patients may require close cardiac monitoring because of existing cardiac disease. If the patient is diabetic, blood glucose levels should be monitored (and corrected) prior to sending the patient to the floor.⁴³ This is also true for patients who are discharged home or to an extended care facility.

Priorities and responsibilities for the nurse in the PACU are numerous. The ultimate priority in the PACU is the ABC, followed by the arousal regimen. The patient is stimulated and encouraged to take deep breaths, thus facilitating the exhalation of any remaining anesthetic agents from their lungs. The second priority for the nurse is to control pain, nausea, and vomiting. Unfortunately, one side effect of administering opioids is nausea and vomiting, thereby creating a balancing act for the nurse. Positioning and warming of the patient is the third priority. The patient is assessed for hypothermia upon arrival, which is a temperature of <96.8°F.⁴⁴ Warm blankets are applied or a forced air warming system may be used until the patient becomes normothermic. The geriatric patient usually has a lower temperature upon arrival and discharge from the PACU than younger patients.⁴⁵ The patient’s preoperative baseline temperature should be noted. If the patient’s temperature is too low, metabolism slows down and excretion of

the anesthetic agents used in the OR may be prolonged, resulting in an increased stay in the PACU.

Vital signs and ECG rhythms should be monitored closely. Many older adults have significant cardiac histories and take medications that influence their cardiac rhythm and their blood pressure. Hypotension may be prolonged in the elderly patient having spinal anesthesia.⁴⁶ The patient's fluid balance can be assessed by observing the abdomen for any signs of bladder distention and monitoring urine output. The lungs should be auscultated and pulses palpated for any indication of fluid overload. The head of the bed should be elevated as appropriate to promote lung expansion. The patient should be encouraged to cough and deep breathe. High-humidity oxygen should be used as needed.

Geriatric patients who are mechanically ventilated may need additional time to meet criteria for extubation. Monitor PaCO₂ levels and assess breath sounds for proper tube placement.⁴⁷ Provide adequate pain control with intravenous opioids, epidural pumps, and/or PCA pump to facilitate extubation. Weaning criteria is met when the patient returns to consciousness, can follow simple commands, has spontaneous respirations, and can sustain a head lift for > 5 seconds.⁴⁷ Necessary personnel and equipment should be available in case reintubation is necessary.

Pain management in the elderly is also a major nursing priority. Uncontrolled pain can lead to cardiac stress, resulting in pulmonary problems and possible myocardial infarction. When medicating the older adult, start low and go slow. Geriatric patients should be assessed preoperatively to determine whether PCA and epidural pain pumps are appropriate. Patient-controlled analgesia and epidural pain pumps may not be the best choice for pain control, depending on the patient's cognitive and physical status. When the elderly patient is placed on a PCA pump or an epidural pain pump, they require consistent and timely assessment and evaluation by the registered nurse. The goal is to progress the patient from intravenous opioids to oral medications as soon as feasible. Oral forms of opioids are often better tolerated in the elderly.⁴⁴ The use of non-steroidal anti-inflammatory drugs (NSAIDs), if not contraindicated, can help reduce the amount of narcotics required. Therefore, NSAIDs, in conjunction with narcotics, should be considered for pain control in the older adult.

Assessment is the key when caring for the postoperative geriatric patient. Vital signs should be checked upon arrival to phase II recovery or upon transfer to the general

nursing unit. The ABCs are still important. Listen to breath sounds and cardiac sounds frequently inspects the surgical site for any bleeding and evaluates all complaints of pain. Palpate peripheral pulses and be aware of the patient's intake and output. In addition to a complete nursing assessment, it is important to listen to all patient complaints and assess them in a timely manner.

POSTOPERATIVE CARE ON THE GENERAL NURSING UNIT

The focus of nursing care of the geriatric surgical patient is to prevent postoperative complications and restore the patient to optimal health. Coughing and deep breathing exercises and the use of the incentive spirometer should be encouraged. The patient should perform these exercises every hour while awake. Support hose and compression devices should be applied as indicated to help prevent the development of blood clots. All surgical patients should be out of bed as soon as possible to prevent complications of immobility (i.e. deep vein thrombosis and atelectasis). Geriatric patients should be ambulated as soon as ordered. Patients should sit on the side of the bed for a few minutes before standing or sitting up in the chair (especially if they take antihypertensive medications) due to the possibility of orthostatic hypotension. Preoperative medications are resumed as ordered and should be verified with the patient or family to be sure no medication has been overlooked.

Assess bowel sounds and start the patient on liquids as soon as indicated. Monitor the patient's bowel movements. The elderly are prone to constipation, especially after surgery, and if taking narcotics. Stool softeners may be ordered postoperatively. Safety is a real issue when caring for the elderly surgical patient. Keep the call light within reach, the side rails up, and the bed in the low position. Remember, sometimes it may take up to 48 hours after surgery for the elderly patient to fully recover from the effects of the anesthetic agents.⁴⁸ Involve family members as much as possible. If the patient has no family, try to place the patient as close to the nurses' station as possible, and have Social Services coordinate arrangements for discharge care and assistance when indicated.

Elderly patients need their rest and periods of uninterrupted sleep. Complete any healthcare treatment about 1 hour prior to sleep. If the patient needs to be aroused during the night for treatments or medications, be sure to schedule periods of sleep at least 2–3 hours in duration.

If the patient requires medication to promote sleep, use the lowest effective dose possible. Promoting comfort in the elderly is where the nurse can be extremely creative. Give analgesics as scheduled and medicate the patient prior to any major dressing changes. Provide back massages and use progressive relaxation techniques with the patient. Keep plenty of extra pillows available for positioning the patient for comfort. Because many elderly patients complain of cold feet, be sure to have the family bring in cotton socks for the patient to wear at night. For the older adult patient who may not have family present, always remember that there is no replacement for the human touch.

PERIOPERATIVE SIDE EFFECTS AND COMPLICATIONS

Major morbidity and mortality after ambulatory surgery are surprisingly rare, even in the elderly population.⁴⁹ According to Fleisher et al.,⁵⁰ in 1997, only one in every 180 patients undergoing an outpatient procedure in New York required hospitalization for inadequate pain control or complications such as bleeding, nausea and vomiting, dizziness, adverse reaction to an anesthetic drug, or an irregular heartbeat. In the same study, only 19 of 783,558 outpatients studied died, a rate of one in 41.⁵¹ Aged >65 years was one of the independent predictors of immediate hospital admission after ambulatory surgery. These data suggest that older outpatients with increasing comorbidities are at increased risk of admission to an inpatient facility after outpatient surgery.

In a large retrospective outpatient outcome study by Chung et al.,⁵² 27% of the patients were >65 years. These investigators reported a 4.0% incidence of adverse events in the OR, 9.6% in the PACU, and 7.9% in the ambulatory surgery unit. Not surprisingly, adverse cardiovascular events were more common in elderly patients with preexisting cardiovascular diseases. Adverse respiratory events in the elderly were usually associated with obesity, smoking, and asthma. In the previously mentioned study by Chung et al.,⁵² older patients were four times less likely to experience any adverse event; 10-fold less likely to complain about excessive pain, shivering, and agitation; and four-fold less likely to develop symptoms of nausea and vomiting and drowsiness in the PACU than were their younger (<65 years) counterparts. It is possible that the elderly are more tolerant of the various stimuli causing side effects such as pain, nausea, and vomiting, or perhaps they are simply more reluctant to complain to their healthcare

providers. These differences may also relate to the different types of surgery and anesthesia between the elderly and younger ambulatory surgery populations in this study. For example, younger patients were more likely to undergo gynecological and orthopedic procedures, which more frequently cause postoperative pain and require the use of opioid analgesic, a factor that can also contribute to the increased incidence of postoperative nausea and vomiting. In contrast, the elderly most commonly underwent ophthalmic procedures, which cause minimal postoperative pain. The latter explanation is supported by the results of a nationwide survey in Denmark involving older (> 65 years) versus young outpatients all undergoing inguinal hernia repair in which the postoperative complication rate was actually significantly higher in the older patients (4.5% vs 2.7%).⁵³

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Surgery of the Sympathetic System: Thoracoscopic Sympathectomy

Sonia Teufack, Joshua E Heller

Snapshot

- » Anatomy and Physiology
- » Indications
- » Surgical Procedure
- » Outcomes and Complications

INTRODUCTION

Surgery to the sympathetic nervous system was first reported in 1889; Alexander performed cervical sympathectomy for the treatment of epilepsy.¹ Over the years, several indications for sympathectomy have been explored and abandoned, namely, idiocy, goiter, glaucoma, and epilepsy.² Sympathectomy still has limited application to certain conditions such as angina pectoris, Raynaud phenomenon, and reflex sympathetic dystrophy.²

In the 1920s, Kotzareff discovered that sectioning of the sympathetic chain resulted in anhidrosis.³ This led to the introduction of sympathectomy for the treatment of hyperhidrosis and flushing. Lumbar sympathectomy for plantar hyperhidrosis became less popular due to high rates of impotence in men. The current workhorse of surgery to the sympathetic system is upper thoracic sympathectomy, adapted into an endoscopic procedure by Hughes in the 1940s and popularized by Claes and Drott in the late 1980s.⁴

ANATOMY AND PHYSIOLOGY

The sympathetic nervous system originates from the hypothalamus and consists of preganglionic cell bodies in the intermediolateral column of the spinal cord from T1 to L2/3. These neurons synapse in the paravertebral ganglia of the sympathetic chain (three cervical, 12 thoracic, and lumbar/pelvis ganglia) and chromaffin cells of the adrenal

medulla. Postganglionic neurons from the sympathetic chain primarily travel with the ventral rami of spinal nerves to target organs.

The sweat response is triggered by an increased core temperature and heightened emotional states such as anxiety and nervousness. The preoptic hypothalamus is responsible for thermoregulation and sends signals through the autonomic nervous system to the eccrine glands, which secrete serous fluid and cool the body by evaporation. Eccrine glands are distributed throughout the skin, but are more abundant in the axilla, palms of the hands, and soles of the feet.

INDICATIONS

The most common current application of sympathectomy is primary axillary and palmar hyperhidrosis. It is an idiopathic overproduction of eccrine glands that affects up to 2.8% of the general population.⁵ Hyperhidrosis can have a significant impact on the quality of life of untreated patients. It can be so severe as to cause sweat to drip off the hands and require several clothing changes per day. This can also affect professional productivity, as simple daily tasks become problematic (handling paper and tools, risk of electric shock for mechanics/electricians, typing on a computer), and result in psychosocial withdrawal and depression.

Hyperhidrosis can result from a secondary process. Patient's workup should exclude conditions such as pituitary and thyroid disease, diabetes mellitus, menopause,

pheochromocytoma, spinal cord injury, certain drugs, and tumors. Important diagnostic criteria of primary focal idiopathic hyperhidrosis include focal, visible, excessive sweating for at least 6 months without secondary cause that include a minimum of two of the following characteristics: positive family history, onset before 25-year-old, frequency of at least once a week, bilateral symmetric perspiration that impairs daily activities, perspiration is absent during sleep.⁶

The first line of treatment is medical, with the use of antiperspirants, anticholinergics, and beta-blockers agents. Botox injection can provide symptomatic relief for 4–9 months at the time. Iontophoresis, also called electromotive drug administration, with tap water or an anticholinergic can be used. However, it requires that the patient dedicates a significant amount of time to therapy daily. Surgical intervention by thoracic sympathectomy is reserved for patients who failed or cannot tolerate non-invasive therapies.

SURGICAL PROCEDURE

Before the introduction of endoscopy, thoracic sympathectomy was performed through several different approaches: posterior, supraclavicular, anterior transthoracic, and transaxillary. The posterior approach, described by Adson for bilateral sympathectomy, requires significant muscle dissection and osteotomies, resulted in debilitating pain and disfiguring scars.⁷ The supraclavicular approach has a difficult exposure of ganglia below T3 and higher incidence of Horner's syndrome (up to 10%).⁸ The anterior transthoracic approach is done through a large incision from the parasternal to the anterior midaxillary line, and requires division of the pectoralis muscle. Finally, the transaxillary approach, the least destructive, has an oblique incision at the base of the axillary hairline from the latissimus dorsi to the pectoralis major.⁹ This approach is still used for patients who cannot or have failed thoracoscopic procedures. The disadvantage is that only one side can be done at the time and it requires a chest tube postoperatively.

Endoscopy revolutionized the procedure by minimizing tissue trauma, improving visualization, and illumination for a more accurate anatomical localization. In addition, both sides can be done in one setting as an outpatient procedure.

Anesthesia

A key point in thoracic surgery is to maintain a deflated ipsilateral lung. This can be achieved through placement of a

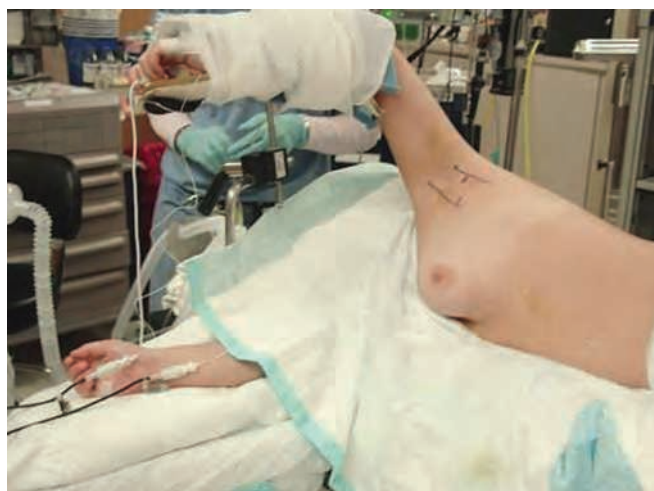


Fig. 10.1: Patient positioning in the lateral decubitus position.

double-lumen endotracheal tube and single lung ventilation. Alternatively, thoracoscopic sympathectomy can be performed with a single lumen endotracheal intubation and CO₂ insufflation to compress the lung. Contraindications may include prior thoracotomy, severe cardiopulmonary disease precluding single lung ventilation, and severe scoliosis.

Instrumentation

The procedure can be done with a 5-mm rigid endoscope, with a lens angle of 0–45° based on surgeon's preference. Other useful instruments include hook electrocautery or harmonic scalpel, long calibrated dissection tools, fan or sponge retractors, and suction irrigation.

Patient Positioning

For bilateral procedures, the patient is positioned supine with his arms at a 90° angle. Next, a 40° reverse Trendelenburg allows the deflated lung to fall away from the surgical site by gravitational pull. Care must be taken to not have the patient slide off the bed. This can be accomplished adjusting the bed to have the patient in a recliner position and using a footboard if necessary (Fig. 10.1).

For unilateral procedures, the patient is positioned in the lateral decubitus position, and is secured with straps and tape.

Approach and Sympathectomy

A 5-mm trochar is introduced in the midaxillary line of the fourth intercostal space. Carbon dioxide is insufflated

as needed, to a pressure of 10 mm Hg. The second port is introduced at the inferior axillary hairline, at the third intercostal space. The first port is used for the endoscope, and the second is the working port.

The sympathetic chain is identified running over the anterior surface of the posterior rib heads (Fig. 10.2). The first rib is not always well visualized but can be palpated. It is associated with a fat pad under that lays the stellate ganglion. Subsequent ganglia are adjacent, slightly caudal to respective rib heads. The second to fourth sympathetic ganglia are identified, the pleural space between ganglia is cauterized over the rib, the sympathetic chain is identified, cauterized and cut above and below the target ganglion. Sectioning of the T2-T3 ganglia is usually performed

for palmar hyperhidrosis, T2-T4 for palmar, and axillary hyperhidrosis. Alternatively, clips can be applied to the sympathetic chain without sectioning (Figs. 10.3A and B). The reversibility of the procedure through removal of clips has recently been debated.¹⁰

The nerve of Kunz represents an intrathoracic ramus that joined the second intercostal nerve to the ventral ramus of the first thoracic nerve, proximal to the point where the latter gave a large branch to the brachial plexus. It is an anatomical variant present in 40–80% of the general population.^{11,12} If present, it needs to be disconnected or excised.

Upon completion of the sympathectomy, a red rubber catheter is inserted in one of the ports, while the other is closed. The catheter is submerged in saline while anesthesia re-expands the lung. Bubbles confirm lung expansion. The red rubber is removed and the second incision is closed. A postoperative chest X-ray is essential to confirm lung expansion and minimal pneumothorax.

OUTCOMES AND COMPLICATIONS

Careful patient selection is the first parameter of a successful surgery. Published series have shown a significant decrease in perspiration for 93.4–100% of patients.² Freeman et al. reported a 6.6–12.5% recurrence of symptoms.² However, their success rate with reoperation was comparable to the initial surgery without significant morbidity.

Variable results have been observed for different ablation levels and techniques. T3 ablations were shown to result in lower incidence or severity of compensatory hyperhidrosis compared to T2 or T2-T4; T4 ablations in

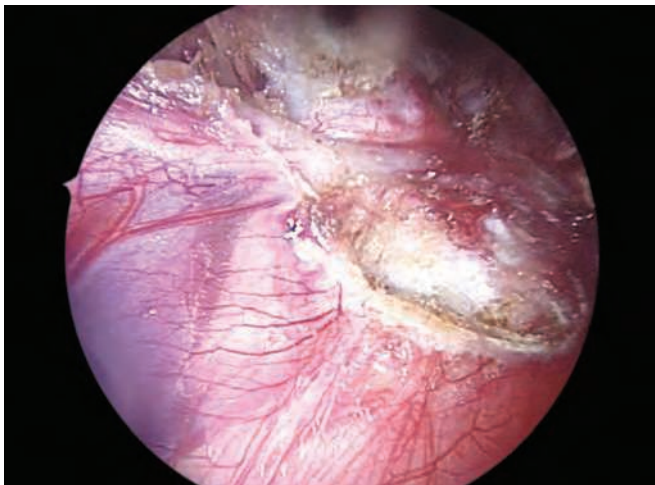
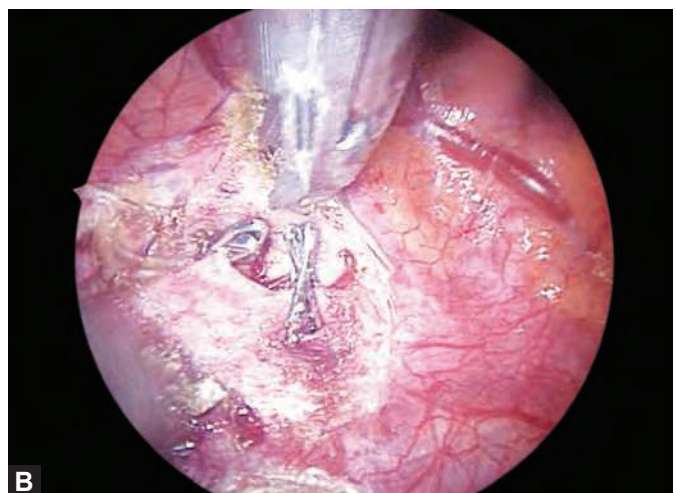
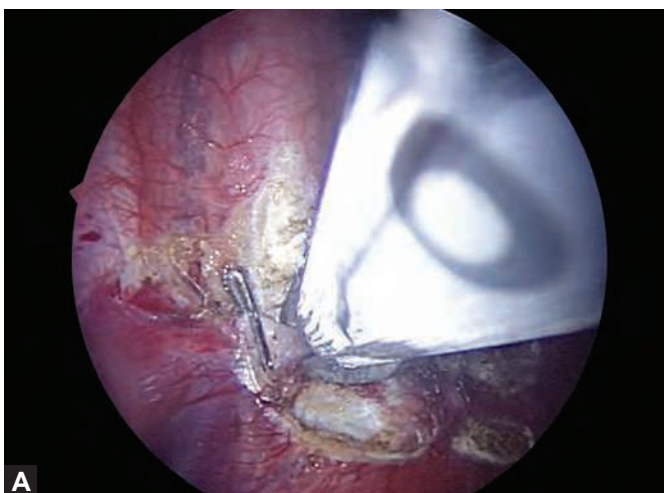


Fig. 10.2: Endoscopic exposure of sympathetic chain.



Figs. 10.3A and B: Endoscopic clip placement on sympathetic chain.

lower incidence of severe anhidrosis.² A systematic review in 2008 revealed no difference in outcome with varying sympathectomy techniques: resection, ablation, and transection.² It also showed that inclusion of T2 in the sympathectomy improved patient outcome and had low rates of compensatory hyperhidrosis.

The most common neurological complication is compensatory hyperhidrosis, reported in 17–75% of patients. However, it usually improves within 6 months and is only severe in 5–10% of cases.² There are currently no conclusive evidence that a specific sympathectomy level reduces the incidence of hyperhidrosis.

Horner's syndrome can result from injury to the stellate ganglion. The incidence is reported as high as 24% in the immediate postoperative period, with long-term symptoms in 0–8% of patients.²

The most common pulmonary complication of thoracoscopic sympathectomy is pneumothorax. It has been reported in 7–17% of cases.² This delays patient discharge and, if symptomatic, may require chest tube placement. Pleural effusions have been reported, particularly in cases where the sympathetic chain was excised as opposed to disconnected. Subcutaneous emphysema in the thorax and neck can occur in up to 2% of cases.²

CONCLUSION

Thoracoscopic surgery is a safe minimally invasive outpatient procedure that can effectively treat primary hyperhidrosis. Patients can have a significant reduction in perspiration and maintain good socioeconomic circumstances.

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Stereotactic Radiosurgery of the Spine

David M Neils, James McGee, Daniel R Fassett

Snapshot

- » Radiobiology
- » Technical Elements of SRS Delivery
- » Toxicity

INTRODUCTION

The role of radiotherapy (RT) in spinal oncology is well established with numerous studies showing the efficacy of RT in relieving pain and preserving functional neurological status from spine metastases.¹⁻³ Traditional RT is delivered via external beam radiation with moderate doses of radiation given over 10–20 fractions, typically on a 5-day per week schedule. Such a schedule may be inconvenient for patients and can delay systemic therapy. Further, standard fractionation, with low dosages of radiation, may not have a sufficient biological effect to control the tumors being treated. Higher doses of conventional RT may not only be more effective in treating the tumor but also put the adjacent neural structures at greater risk. Advances in planning software, target immobilization, imaging at the

time of treatment to ensure accuracy, and speed of radiation delivery allow many patients to safely receive higher doses of radiation per treatment for a greater biological effect while protecting radiosensitive adjacent tissues.⁴

Stereotactic radiosurgery (SRS) of the spine is a single high dose of radiation carefully shaped to the tumor target and given with imaging of the patient's internal anatomy (or implanted surrogate fiducial markers) to assure accurate dose targeting. Stereotactic body radiotherapy (SBRT) is a hypofractionated RT course typically consisting of two to five fractions whose dose is higher than traditionally delivered per fraction.⁴ The differences in the delivery of these forms of RT are summarized in Table 11.1. The basic premise of both SRS and SBRT is the delivery of radiation in such a manner to achieve a better clinical control of the tumor with fewer side effects and increased efficiency.

Table 11.1: Types of radiotherapy.

Therapy	Number of doses	Doses per fraction	Comments
Conventional radiotherapy	10	300 cGy	Split course
	5 + 5	500 cGy + 300 cGy	
Hypofractionated stereotactic body radiotherapy	4	4 Gy	All considered equivalent
	5	6 Gy	
	3	8 Gy	
	3	9 Gy	
Stereotactic radiosurgery	1	16–24 Gy	

By using image guidance and highly conformal doses, the radiation oncologist is able to target abnormal tissue but have a rapid dose falloff that will allow for tolerable doses of radiation to the surrounding normal tissues. Stereotactic radiosurgery and SBRT are similar in concept and delivery. The dose to the surrounding normal tissues, including the spinal cord, is often the deciding factor in the choice of conventional fractionation, single-fraction radiosurgery, or two to five fractions SBRT. The terms SRS and SBRT are often used interchangeably (i.e. five fraction radiosurgery) leading to some confusion in the literature. It is important to note that the radiation tolerance of normal tissues varies significantly as the number of fractions and time course of therapy change. So too, the chances of tumor control and the speed of symptom relief vary with the dose and time factors. Such variations need to be considered when outcomes in the literature are used to compare SRS, SBRT, conventional RT (with a greater number of fractions), and open surgical treatment.

The indications for treatment with SRS and SBRT are similar to the indications for conventional RT. The goals are typically palliation of pain, local disease control, and prevention of (or selectively reversing) neurological deficits.⁵ Current applications of these techniques are as single modality treatment for spinal metastases or as a salvage option for previously treated tumors, by either prior radiation⁶ or surgical resection. Increasingly, patients are treated with SRS or SBRT after surgical debulking of a portion of tumor. For tumors encroaching upon the spinal canal, surgical debulking can remove the tumor in close proximity to the spinal cord and allow for a safe radiosurgical dosage of radiation to the remaining tumor.

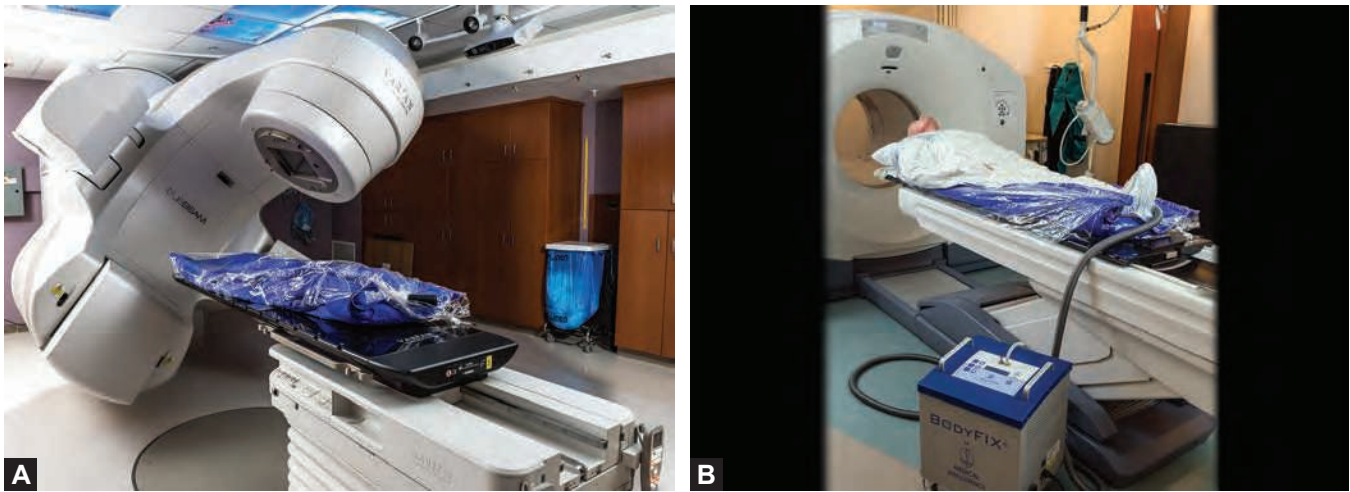
Stereotactic radiosurgery and SBRT have a number of advantages compared with conventional RT in the treatment of metastatic disease. The first significant advantage is that a higher dose of radiation delivered in a single setting will have a greater radiobiological impact upon the tumor, thereby broadening the spectrum of pathology amenable to treatment to include malignancies traditionally considered to be radioresistant such as melanoma, renal cell carcinoma, and sarcoma. Second, delivery of radiation with a rapid falloff of dose can reduce the complications related to RT such as esophagitis or radiation-induced myelopathy. Importantly for surgeons, the highly conformal nature of SRS allows for sparing of the skin and surrounding soft tissues, decreasing the risk of poor wound healing, and allowing earlier administration of radiation in the post-

operative patient. The smaller fields used in SRS and SBRT also lead to less bone marrow suppression with its adverse effects upon the utilization of chemotherapy. Finally, SRS and hypofractionated treatments are more convenient for patients in comparison to weeks of daily treatments with conventional RT.

RADIOBIOLOGY

Radiobiology is the study of the manner in which radiation interacts with living cells. As a result of a longer history of the application of SRS to cranial pathologies, most of the clinical advantages of SRS in other locations in the body are inferred from years of cranial radiosurgery experience. Radiation doses, as delivered in conventional fractionation, lead to free-radical formation largely mediated by oxygen in the tissues. Conventional RT typically induces death in target cells by means of double-strand deoxyribonucleic acid (DNA) breaks.⁷ These double-strand breaks can ultimately lead to cell death. Conventional RT is effective when tumor cells are more sensitive to the treatment than the surrounding normal tissues. The relative radioresistance of some pathologies may reflect their ability to repair the damage that ionizing radiation does to their DNA. Pathologies that are resistant to radiation typically are tumors that are able to repair the damage done to their DNA by the relatively small daily exposures delivered by the conventional RT. Conventional RT is also dependent upon the varying sensitivity of cells to radiation damage based upon their place in the cell reproductive cycle with radiosensitivity decreasing during the times when the DNA is not undergoing active synthesis or mitosis.

Stereotactic radiosurgery delivers a much higher dose effect in a shorter time frame, changing the radiobiology compared with that of conventional RT. While DNA effects are still important, additional mechanisms of cell death are undoubtedly involved. Higher doses per fraction impact the vascular endothelium. Inferring from the cranial experience with SRS on arteriovenous malformations, doses >10 Gy in a single fraction have a marked influence on vascular endothelium that is not seen with conventional radiation dosing.⁸ The end result of exposure to high-dose ionizing radiation is endothelial hypertrophy and obliteration of the microvascular tumor environment. This data is supported by animal models analyzing the effects of radiation.⁹ Other equally important mechanisms of enhanced tumor cell killing with radiosurgery are being studied.¹⁰



Figs. 11.1A and B: Patient immobilized for stereotactic radiosurgery treatment on Trilogy system.

TECHNICAL ELEMENTS OF SRS DELIVERY

Advances in target planning, immobilization, radiation delivery, and target motion tracking have led to the precision necessary for the delivery of SRS.⁴ There are a number of commercially available systems for the delivery of SRS/SBRT. These systems include Novalis, TomoTherapy HI-ART Helical Tomotherapy, CyberKnifeElekta Synergy S, and Varian Medical Systems Trilogy and TrueBeam linear accelerators with RapidArc. The patient's body and subsequently the target are immobilized by different techniques based upon the commercial system. Common ways of immobilization are masks for cervical pathology and conformational body support for thoracic and lumbar pathologies.⁴ An example of a patient immobilized for radiosurgery is shown in Figures 11.1A and B.

Planning for SBRT/SRS is typically undertaken by a multidisciplinary team including spine surgeons, radiation oncologists, and medical physicists. The preprocedural workup should include either computed tomography (CT) scan or magnetic resonance imaging (MRI) to accurately identify the target pathology as well as the important surrounding anatomy including the spinal cord and esophagus. Computed tomography myelography for radiation treatment simulation is indicated to accurately locate the spinal cord or spinal nerve roots in planning for tumors that are in close proximity to the spinal cord. In some instances, 3D image fusion of CT and MRI data in the radiation treatment planning systems may be adequate for the identification of the important anatomy. Image fusion can result in some imprecision that must be considered if tumor is

in proximity to critical neurological structures such as the spinal cord. Imaging studies must be obtained to allow for optimal delineation of the tumor extent as well as organs at risk for radiation injury from treatment. In conventional RT, surrounding normal tissues are covered by the radiation treatment. Although this can lead to damage to surrounding normal tissues, it could potentially be beneficial in situations when the tumor is invading the surrounding tissues. Radiosurgery demands detailed contouring to include all areas of tumor extension as well as exact location of critical normal structures that can be damaged by high dose per fraction radiation. The exact specifics on planning will vary with the commercially available system used to administer SRS.

Target Planning

In order to effectively administer SRS, the treating physician(s) must develop a treatment plan. This must be done manually by the treating team by defining the tumor as well as any adjacent organs at risk for radiation damage on pertinent imaging studies. Three important volumes are commonly defined for tumor volumes: gross tumor volume (GTV), clinical target volume (CTV), and planning target volume (PTV). The International Spine Radiosurgery Consortium established guidelines for the definition of these three important volumes as summarized in Table 11.2. Gross tumor volume is the contoured volume of the tumor based upon available imaging studies. Clinical target volume is the volume surrounding the GTV suspicious for microscopic disease spread. The PTV is an intentional circumferential expansion around the CTV to account

Table 11.2: Important clinical volumes in stereotactic radiosurgery.

Target volume	Included
Gross tumor volume (GTV)	Contour gross tumor based upon all imaging including epidural and paraspinal components
Clinical target volume (CTV)	GTV plus abnormal bone marrow signal and a expansion of bony GTV to account for microscopic and subclinical tumor spread
Planned target volume (PTV)	Uniform expansion of CTV of 3 mm or less, this should be contoured to avoid spinal cord and should contain both the GTV and CTV

Source: Adapted from Cox BW, Spratt DE, Lovelock M, et al. International Spine Radiosurgery Consortium consensus guidelines for target volume definition in spinal stereotactic radiosurgery. *Int J Radiat Oncol Biol Phys.* 2012;83(5):e597-605.

for setup inaccuracy specific to the system and patient being treated, often a margin of 1–3 mm. The PTV is the volume to which radiation delivery is planned.¹¹ The circumferential expansion of the PTV must be well considered and cannot include the spinal canal or adjacent esophagus in the PTV.

Radiosensitive structures typically considered at risk given their proximity to spine include the spinal cord, cauda equina, nerve roots, esophagus, trachea, oropharynx, and kidneys. As the dose per fraction increases, other organs have to be considered for both acute and long-term effects, including the bowel. All of these organs have varying radiation tolerances as the dose per fraction and the number of fractions change. Organ tolerance and complications are discussed in detail in the toxicity section. An example of a planning simulation is shown in Figures 11.2A and B.

Spine SRS for Metastatic Pathology

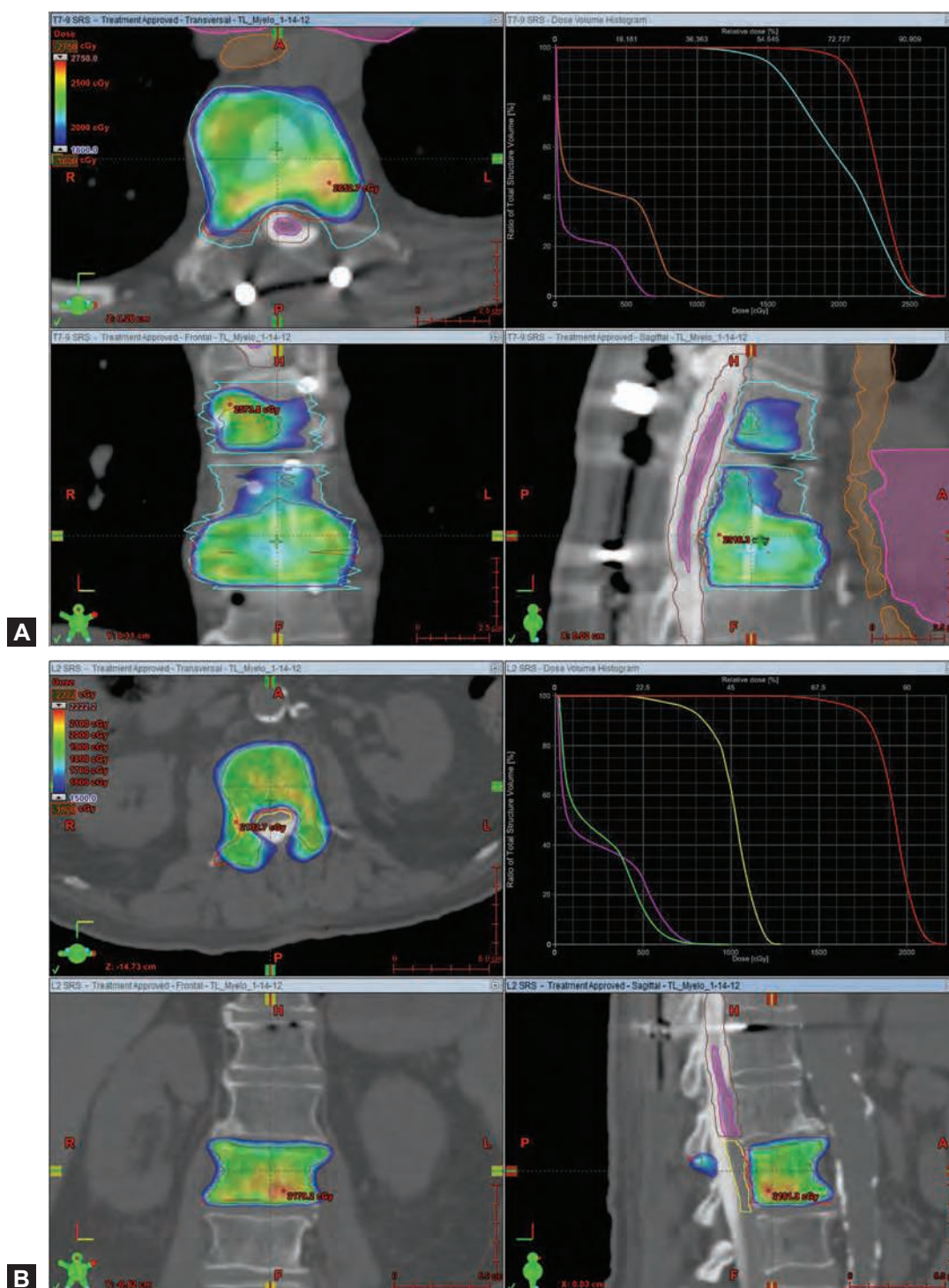
The decision to apply SRS to a particular lesion is similar to other oncologic decisions in that tissue histology of the lesion is the cornerstone of decision making. This is the result of the variable sensitivity of various primary histologies to radiation treatments as is summarized in Table 11.3.⁵ As shown in the table, histologies range from relatively radiosensitive (favorable pathologies) to relatively radioresistant (unfavorable pathologies). In general, lymphoma, seminoma, small cell lung carcinoma, myeloma, and other nonsolid organ tumors are classified as very

radiosensitive tumors and are often excluded from surgical and radiosurgical studies. At the other end of the spectrum are the relatively radioresistant tumors, which typically include sarcoma, melanoma, gastrointestinal tumors, nonsmall cell lung carcinoma, and renal cell carcinoma. Intermediate range tumors typically include breast and prostate carcinoma. As a rule of thumb, conventional RT is the frontline treatment of radiosensitive metastatic tumors. In the setting of intermediate and resistant tumors, multidisciplinary decision making is recommended with consideration for a combination of conventional surgery, SRS, and conventional RT depending upon the condition of the patient and the experience of the treating team.

The effect of SRS on particular pathologies has not been systematically studied to this point, and the best available data is from large prospective cohort studies.¹² This data is difficult to interpret related to the heterogeneity of the metastatic spinal tumor patient population. Patients often present to SRS centers having undergone highly variable pretreatment management. Additionally, patient characteristics such as performance status and chemotherapy treatments can be confounding variables in assessing data from trials involving patients with advanced metastatic disease. Given these difficulties, the best available analysis of these cohort studies comes from literature reviews. For local tumor control SRS ranged from 75% to 100% effective, while for pain control/improvement SRS was 36–97.3% effective. In this same literature, SRS produced side effects in the form of radiation-induced myelopathy in 0–4% of cases. The data on the treatment of malignant pathologies with spinal SRS is summarized in Table 11.4. Both the rate of local recurrence and radiation-induced myelopathy are dependent upon the delivered dose of radiation, a single dose of at minimum 15.1 Gy to the GTV was associated with 100% local control in a study of 79 patients with 91 consecutive tumors.¹³

Spinal SRS for Primary CNS Pathologies

Spinal SRS is predominantly applied to malignant pathologies as metastases account for the greatest percentage of tumors in the spinal column. However, based upon the experience gained with cranial radiosurgery, primary lesions of the spinal column are being studied for SRS treatment. The initial experience with cranial stereotactic radiosurgery has demonstrated the effectiveness and safety of SRS for trigeminal neuralgia,²⁹ arteriovenous malformations,³⁰ and multiple types of benign intracranial tumors.^{31,32}



Figs. 11.2A and B: Treatment plan from a 67-year-old man with a history of metastatic melanoma. The patient had multiple lesions including a pathological burst fracture of T9 and lesions in T3, T8, and L2. The treatment plan utilized a computed tomography myelogram to better localize the spine cord. A magnetic resonance imaging (MRI) was also fused with this myelogram to help localize the tumors, but the MRI images are not shown here. (A) Plan for the T9 and T8 tumors is shown. Note the presence of methylmethacrylate (bone cement) and Steinman pin in the area of the T9 vertebral body and the pedicle screws with rods posteriorly. The spinal cord is depicted in purple, the esophagus is shown in orange, and the tumor is blue-green. (B) Plan for L2 metastasis is shown with the spinal cord (purple), cauda equine (yellow), and tumor (blue) outlined.

Table 11.3: Radiosensitivity based upon histology.

<i>Histology</i>	<i>Sensitivity</i>
Lymphoma	Radiosensitive
Seminoma	Radiosensitive
Myeloma	Radiosensitive
Small cell lung	Radiosensitive
Breast	Intermediate
Prostate	Intermediate
Sarcoma	Radioresistant
Melanoma	Radioresistant
Gastrointestinal	Radioresistant
Nonsmall cell lung	Radioresistant
Renal	Radioresistant

Source: Adapted from Gerszten PC, Mendel E, Yamada Y. Radiotherapy and radiosurgery for metastatic spine disease: what are the options, indications, and outcomes? *Spine* (Phila Pa 1976). 2009;34(22 Suppl):S78-92.

Two separate large studies have been published utilizing spinal SRS for benign intradural extramedullary pathology.^{33,34} The results based upon pathology are summarized in Table 11.5. Overall these studies have shown the safety of SRS for these pathologies with 4%³³ and 1%³⁴ of treated intradural tumors developing symptoms referable to radiation-induced myelopathy. These studies also demonstrate the durability of SRS for meningiomas, schwannomas, and neurofibromas with only a single case of radiographic progression in the 176 pooled tumors over follow-up ranging from 8 to 87 months. Stereotactic radiosurgery has also been used to treat sarcomas,³⁵ hemangioblastomas,³⁶ and chordomas.³⁷

Spinal SRS as Adjuvant Treatment to Surgery

Metastatic disease is the most common indication for the use of SRS, but the application of this technique has not

Table 11.4: Spinal stereotactic radiosurgery for metastatic tumors.

<i>Author</i>	<i>Year</i>	<i>Number of patients</i>	<i>Histology</i>	<i>Local control rate</i>	<i>Pain control</i>
Benzil ¹⁴	2004	26	Multiple	NA	94%
Chang ¹⁵	2007	63	Multiple	84% progression free at 1 year	NA
Degen ¹⁶	2005	38	Multiple	100% in tumors not previously irradiated	97.3% VAS decreased from 51.5 to 21.3 at 4 weeks, remained at 17.5 at 1 year
Gagnon ¹⁷	2009	151	Multiple	NA	38% pain free following treatment 1 month VAS improved by a mean of 19
Gerszten ¹²	2007	393	Multiple	89% local control	86% pain improvement
Gerszten ¹⁸	2005	48	Renal cell carcinoma	87% local control	89% pain improvement
Gerszten ¹⁹	2005	28	Melanoma	75% local control	96% pain improvement
Gerszten ²⁰	2005	50	Breast	100% local control	96% pain improvement
Gerszten ²¹	2006	77	Lung	100% local control	89% pain improvement
Gibbs ^{22,24}	2007	74	Multiple	NA	84% of symptomatic patients had improvement in symptoms (pain/deficit)
Jin ²³	2007	196	Multiple	NA	38% complete and 47% partial pain relief at 4 weeks
Ryu ²⁵	2008	49	Multiple	NA	46% complete, 18.9% partial pain relief Overall 1-year pain control was 84%
Ryu ²⁶	2004	49	Multiple	NA	85% complete or partial pain relief
Wowra ²⁷	2008	102	Multiple	98% local control at 15 months	VAS from 7 to 1
Yamada ²⁸	2008	93	Multiple	90% local control at 15 months	NA

(VAS: Visual analog score).

Table 11.5: Spinal stereotactic radiosurgery for benign intradural lesions.

<i>Study, Year</i>	<i>Histology</i>	<i>N (No. of tumors)</i>	<i>Average prescribed tumor dose</i>	<i>Radiographic response</i>	<i>Clinical response/pain control</i>	<i>Follow-up</i>	<i>Complications</i>
Gerszten et al., 2008 ³³	Overall	73	2164 cGy (1500–2500)	100% progression free	73%, 22/30 cases had improvement in pain	8–71 months	3 cases of spinal cord toxicity at 5–13 months
	Meningioma	13	2125 cGy (1750–2500)				
	Neurofibroma	25	2130 cGy (1500–2500)				
	Schwannoma	35	2203 cGy (1750–2500)				
Sachdev et al., 2011 ³⁴	Overall	103	19.4 Gy (14–30)	Actuarial control rate of 95% at 4 years		6–87 months	1 case of transient myelopathy at 9 months
	Meningioma	32			57% improved, 43% unchanged		
	Neurofibroma	24			17% improved, 50% minimal change, 33% worsened		
	Schwannoma	47			53% improved, 36% minimal change, 14% worsened		

yet been fully realized with many patients still being seen for “salvage” therapy after failing conventional RT. Most studies also indicate that for radioresistant and intermediate sensitivity tumors, the response time and duration of symptom relief is much better for radiosurgery than conventional RT. Stereotactic radiosurgery is also being increasingly utilized as an adjunct to surgical decompression and/or stabilization.

Following surgical treatment of metastatic spinal disease, the technical delivery mechanisms of SRS/SBRT have the advantage of less radiation to the skin and theoretically fewer wound breakdown problems. This allows for earlier treatment of patients after open surgical procedures with high local control rates. Itshayek et al.³⁸ recently reviewed the timing of RT following surgical treatment of metastatic disease. This review found no study definitively addressing this issue but recommend based upon the physiology of wound healing that RT be delayed at least 1 week following surgery. Another concern in the postoperative patient is the concern for instrumentation failure, a single retrospective study³⁹ compared instrumentation

failure in SRS and RT and found a nonsignificant 0% versus 43% instrumentation failure rate for SRS and RT adjuvant treatments respectively. Moulding et al.⁴⁰ reviewed their experience with high dose 24 Gy single fraction treatments following surgical excision and found a 1-year local failure rate of 6.3% compared with 20% in patients treated to 18–21 Gy. There were no cases of wound healing problems in this study.

TOXICITY

The maximum dose that can be delivered to a tumor with radiosurgery is typically limited by the maximum safe dose to surrounding structures. In most cases of spinal stereotactic radiosurgery, the most sensitive structure is the spinal cord. There are a number of different methods for planning a treatment to minimize adverse effects on the spinal cord including a maximum point dose to the spinal canal or thecal sac. The spinal cord is, like other CNS tissues, increasingly more at risk for radiation damage as the dose per fraction that it receives increases. In radiobiology, this is expressed as a low alpha/beta ratio. The alpha/beta ratio

Table 11.6: Adjacent tissue tolerance.

<i>Tissue</i>	<i>Volume (mL)</i>	<i>Volume max (Gy)</i>	<i>Max point dose (Gy)</i>
<i>Single fraction</i>			
Spinal cord	<0.025	10	14
Cauda equina	<5	14	16
Esophagus	<5	14.5	19
Great vessels	<10	31	37
Trachea	<4	8.8	22
Skin	<10	14.4	16
Lung	1500	7	
Renal	200	8.4	
<i>Three Fraction</i>			
Spinal cord	<0.25	18	22
Cauda equina	<5	21.9	24
Esophagus	<5	21	27
Trachea	<4	15	30
Renal hilum	<2/3 volume	18.6	
Lung	1500	10.5	
Renal cortex	200	14.4	

Source: Adapted from Timmerman RD. An overview of hypofractionation and introduction to this issue of seminars in radiation oncology. *Semin Radiat Oncol.* 2008;18(4):215-22.

for CNS tissues is among the lowest in the body. Stereotactic radiosurgery and SBRT are only safe if the dose to the spinal cord is accurately known and restricted both in the treatment planning and in dose delivery. The spinal cord is a serial organ, not a parallel organ, and consequently any portion of the cord at any level being damaged is a major complication. Ryu et al.⁴¹ examined the effect of SRS on the spinal cord volume defined as a volume 6 mm above and below the tumor volume and had a single case of radiation-induced myelopathy in 86 patients who survived a year. They concluded from this experience that a dose of 10 Gy to 10% of the spinal cord above and below the tumor volume is safe. Another means of defining spinal cord tolerance is as a point tolerance. Sahgal et al.⁴² examined 5 cases of radiation-induced myelopathy with 19 matched patients and concluded that using maximum point dose measurements 10 Gy in a single fraction is safe and up to 5 fractions with a biologically effective dose of 30–35 Gy with an α/β of 2/2 to the thecal sac is safe. We recommend the use of maximum dose points, not volumes of cord, given the consequences of cord injury. Timmerman⁴³ published the dose constraints used in SBRT, the

data of which has been adapted to spine SRS adjacent organs in Table 11.6.

CONCLUSION

Stereotactic radiosurgery or SBRT are viable options in the treatment of metastatic disease to the spine. The treatment has been shown to be both safe and effective at both pain control and local tumor control. The exact role of SRS as the initial treatment of metastatic disease, as salvage therapy for failed conventional RT, and as an adjuvant to conventional surgical treatment is not fully defined; however, the treatment has been shown to be safe and effective in all of these settings. Stereotactic radiosurgery holds promise in the treatment of relatively radioresistant tumors by delivering a higher dosage of radiation and providing additional pathways for tumor cell death compared with conventional RT. Future studies will continue to delineate the optimal dosing strategies in different pathologies and clinical situations.

KEY POINTS

- Advances in imaging, targeting, and radiation delivery have allowed for the precise delivery of highly conformal radiation to the spine.
- Stereotactic radiosurgery and SBRT are typically reserved for patients who have failed conventional RT, or who have radioresistant tumors.
- Stereotactic radiosurgery/stereotactic body RT have been shown to be 75–100% effective at local metastatic tumor control and 36–97% effective for pain control in metastatic disease.
- There is an increasing role for SRS/SBRT in the treatment of primary spinal tumors including meningioma, schwannoma, ependymoma, chordoma, sarcoma, and hemangioblastoma.
- Stereotactic radiosurgery/stereotactic body RT has been shown to have a low toxicity/complication rate as long as targets are carefully planned to limit the dose to the spinal cord.

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Excellent general review of stereotactic body radiation treatments. This article focuses on indications, a review of the literature, toxicity, and limitations of radiosurgery of the spine.

Gerszten PC, Mendel E, Yamada Y. Radiotherapy and radiosurgery for metastatic spine disease: what are the options, indications, and outcomes? *Spine (Phila Pa 1976).* 2009;34(22 Suppl):S78-92.

This is an excellent review of stereotactic radiosurgery. This review examines the role of SRS and conventional RT in the treatment of patients with metastatic spine disease.

Gerszten PC, Burton SA, Ozhasoglu C, et al. Radiosurgery for spinal metastases: clinical experience in 500 cases from a single institution. *Spine (Phila Pa 1976).* 2007; 32(2):193-9.

This is a large prospective cohort study reporting the outcomes and complications of the University of Pittsburgh's experience with single fraction spinal radiosurgery.

Sahgal A, Ma L, Gibbs I, et al. Spinal cord tolerance for stereotactic body radiotherapy. *Int J Radiat Oncol Biol Phys.* 2010;77(2):548-53.

This is a small case series of patients who developed radiation-induced myelopathy. The paper suggests a maximum dose of 10 Gy to any point on the spinal cord to limit toxicity in single fraction treatments.

Intraoperative Neuromonitoring during Spine Surgery

Adam T Doan, Maurice L Goins, Richard W Vogel, Anthony K Sestokas

Snapshot

- » Developing the IONM Plan
- » Transcranial Electric Motor Evoked Potentials
- » Somatosensory Evoked Potentials
- » Electromyography
- » Brainstem Auditory Evoked Potentials
- » Other Neuromonitoring Modalities
- » Implementing and Optimizing IONM
- » Mechanisms of Injury and Review of Intervention Strategies
- » IONM during Cervical Spine Surgery
- » IONM during Anterior Cervical Spine Surgery
- » IONM during Posterior Cervical Spine Surgery
- » Additional IONM Considerations during High Cervical Spine Surgery
- » IONM during Posterior Thoracic Spine Surgery
- » IONM during Anterior Thoracic Spine Surgery
- » IONM during Lumbosacral Spine Surgery
- » IONM during Posterior Lumbosacral Spine Surgery
- » IONM during Anterior Lumbosacral Spine Surgery

INTRODUCTION

One of the most feared complications in spinal surgery is neurological injury. Although an infrequent occurrence, iatrogenic neurological injury can be a devastating complication leading to serious sequelae and possible permanent impairment. In recent decades, there has been much technological advancement in spine surgery leading to a broader role for treatment of complex spinal pathologies with surgery and improved outcomes. Intraoperative neurophysiological monitoring (IONM) has played an integral role in this advancement. In recent decades, IONM has expanded in scope, finding application in a wide range of surgical procedures where there is elevated risk of neural compromise. Primarily, IONM serves to prevent or minimize neurological sequelae by providing a pathway of early intraoperative detection of evolving neurological injury. Intraoperative neurophysiological monitoring is based on the premise that neurophysiological activity changes in a measurable and reversible way before the onset of

permanent neurological deficit, thus opening a window of opportunity for correction.¹

As it applies to spine surgery, IONM first emerged from the laboratory setting and was initially utilized to detect impending iatrogenic injury of the spinal cord during pediatric deformity correction.²⁻⁶ As innovations in spinal instrumentation paved the way for surgical advancements, neuromonitoring technologies evolved in parallel and allowed surgeons to become more aggressive with their therapeutic goals and techniques.^{7,8} While these advancements in surgical techniques enjoyed a high success rate for deformity correction, they were not without their share of neurological complications. Indeed, these complications were highlighted in a report by the Scoliosis Research Society, which chronicled the potential for acute neurological deficit associated with these new techniques.⁹

Initially, intraoperative monitoring of spinal cord function was limited to survey of the somatosensory tracts. The first intraoperative evaluations of motor function consisted of a wake-up test, wherein anesthesia was reversed

to the point at which the patient could volitionally move his extremities.¹⁰ There were many logistical difficulties associated with the Stagnara wake-up test such as reversing anesthesia, having the patient follow commands on the operating table, reintroducing anesthesia and not the least of which was not allowing for continuous monitoring of motor function. The inability to continuously monitor motor function was a void in IONM, limiting its usefulness throughout surgery. This void was filled with the discovery that transcranial electrical stimulation of the motor cortex produced recordable potentials in contralateral muscles.¹¹ Boyd and colleagues¹² adapted the technique for monitoring corticospinal tract function during surgery. Subsequent advances in monitoring equipment, anesthesia protocols,¹³ and methodology¹⁴ have allowed for routine continuous monitoring of spinal cord motor tract function during spine surgery.

Risk of neurological injury may extend beyond the spinal cord to include nerve roots. Spontaneous electromyography (EMG) was introduced to spine surgery in the early 1990s as a means of detecting nerve root irritation in real time.^{15,16} Other advances included adaptation of EMG techniques to test for medial pedicle wall breaches following pedicle screw placement.^{17,18} Given the complex nature of spine surgery, individual monitoring modalities cannot adequately survey all at-risk neural elements. Thus, a multimodality IONM approach is required for comprehensive neurophysiological surveillance and has gained increased acceptance in recent years.¹⁹⁻²²

DEVELOPING THE IONM PLAN

The neuromonitoring plan must be developed as an individualized patient-specific plan that encompasses the entirety of the patient's medical history, present pathology, and the plan of treatment. Because IONM data are influenced by a wide range of factors, the patient's medical history should be thoroughly reviewed by the neurophysiologist prior to surgery. A bedside examination should include objective assessments of strength, light touch, proprioception, reflexes, and cranial nerve motor functions. All preexisting neurological deficits should be documented. A chart review should also be conducted in order to identify factors in the patient history that could adversely influence the quality of neuromonitoring data. Some influencing patient factors of particular importance are neuromuscular and neurodegenerative diseases, diabetes mellitus, hypotension/hypertension, stroke, radiation therapy, abnormal blood panels (e.g. low hemoglobin or high creatinine), and

prior surgery involving the brain, spine, or joints. Finally, the neurophysiologist should review radiographic imaging to integrate pathology with presentation. Each IONM test modality measures the functional integrity of a different part of the nervous system, with little overlap. As such, test modalities are selected after at-risk elements of the nervous system have been identified.^{1,23}

TRANSCRANIAL ELECTRIC MOTOR EVOKED POTENTIALS

Transcranial electric motor evoked potentials (tceMEPs) are used to monitor the integrity of efferent spinal cord pathways mediating motor function, particularly the corticospinal tract. Typically, intramuscular needle electrodes are used to record myogenic responses to anodal electrical stimulation of contralateral primary motor cortex.^{11,12} Myogenic tceMEPs are highly sensitive to acute changes in spinal cord motor function.²⁴⁻²⁶ While there is no universal consensus on warning criteria for significant change,^{27,28} tceMEP amplitude attenuation >65% from baseline that cannot be explained by technical or anesthetic factors warrants prompt surgical attention.²⁶ Figure 12.1 illustrates how appropriate identification and timely reversal of the proximate cause of tceMEP change can result in the recovery of motor conduction and avoidance of postoperative neurological deficit. Myogenic tceMEPs are also sensitive to the effects of anesthesia, particularly inhalational agents, because they require depolarization at multiple synapses throughout the nervous system, including local interneurons of the cerebral cortex, and α -motoneurons of the spinal cord.^{29,30} An alternative, but more invasive, technique for monitoring spinal cord motor function is recording the neurogenic D-wave. In response to motor cortex stimulation, descending volleys are recorded with an epidural or subdural electrode situated over the dorsomedial surface of the spinal cord. D-waves are stable, reliable, and highly resistant to anesthetic effects because they are mediated asynchronously.^{12,31}

SOMATOSENSORY EVOKED POTENTIALS

Somatosensory evoked potentials (SSEPs) are used to monitor the functional integrity of spinal cord sensory tracts specific to the dorsal column-medial lemniscus system. Electrical stimulation of ulnar or median nerves activates the cuneatus tract, while peroneal or posterior

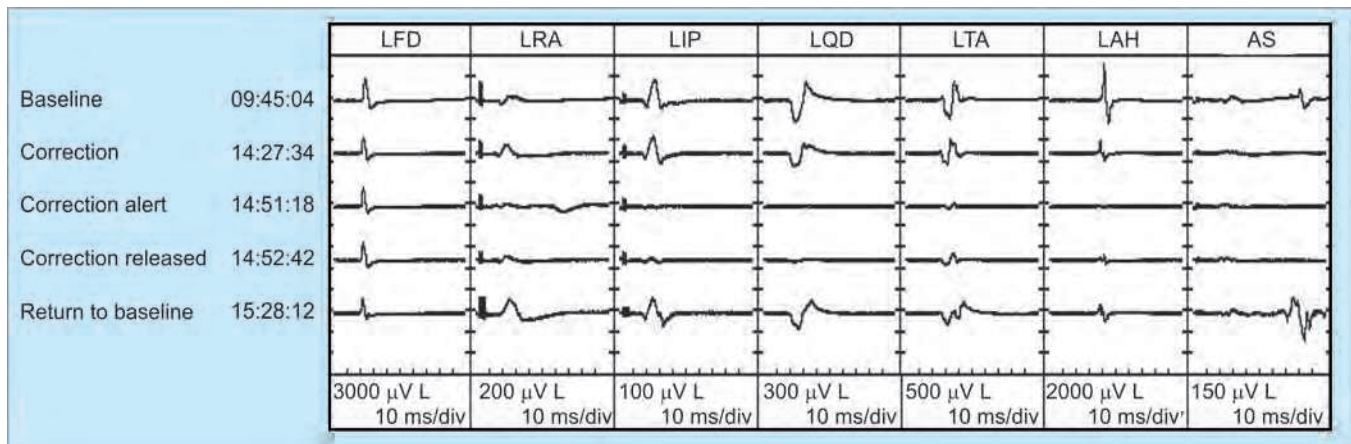


Fig. 12.1: Reversible transcranial electric motor evoked potential (tceMEP) attenuation during posterior T2-L4 instrumented fusion with pedicle screw fixation for idiopathic scoliosis, demonstrating effect of intervention following neuromonitoring alert. Transcranial electric motor evoked potentials were of sufficient size and consistency for reliable monitoring at baseline and just prior to correction of the deformity. During the course of correction, tceMEPs from all left side myotomes below the level of correction exhibited marked amplitude attenuation with no concomitant change in SSEPs, right side tceMEPs, mean arterial blood pressure, or depth of anesthetic hypnosis. Following a surgical pause and increase in the MAP from 73 to 93 mm Hg, tceMEPs gradually improved and were consistent with baseline by closure. This procedure was staged, and the deformity was corrected at a later date without compromise of neurological function. (FD: First dorsal interosseous; RA: Rectus abdominis; IP: Iliopsoas; QD: Quadriceps; TA: Tibialis anterior; AH: Abductor hallucis; AS: External anal sphincter; Prefix L indicates the left side).

tibial nerve stimulation activates the gracilis tract, resulting in subcortical responses recorded with surface or subdermal needle electrodes placed near the second cervical vertebra and cortical responses recorded with electrodes placed in the scalp over somatosensory cortex.³² Cortical SSEPs are particularly susceptible to inhalational anesthetic agents, while subcortical SSEPs are more resistant.²⁹ Somatosensory evoked potential amplitude attenuation >50% from baseline that cannot be explained by technical or anesthetic factors warrants prompt surgical attention.^{33,34} Because SSEPs reflect dorsal column function, they may remain unchanged in the face of evolving motor deficit.^{26,35} The dorsal columns can be mapped in order to identify the median raphe of the spinal cord when a dorsal myelotomy is planned. Intramedullary tumors can distort the anatomy of the dorsal spinal cord, making it difficult to identify the posterior median sulcus visually. Dorsal column mapping (DCM) will identify the electrophysiologic midline, allowing the surgeon to perform a myelotomy that can largely spare dorsal column function. There are a number of ways to perform DCM. If a 6–8 lead electrode strip is placed across the spinal cord in the transverse plane, one can stimulate the spinal cord selectively and record SSEPs from the scalp, using phase reversal to identify the midline.³⁶ This same electrode could be used to record dorsal column volleys in response to peripheral nerve stimulation.³⁷ Finally, one can stimulate the dorsal spinal

cord and record antidromic responses from the peripheral nerves.³⁸ While each of these techniques can be technically challenging, their potential for reduction of postoperative morbidity of dorsal column function is promising.

ELECTROMYOGRAPHY

Intraoperative EMG is used to monitor somatic efferent nerve activity and can be used to accurately assess the functional integrity of individual nerves when they are subjected to direct electrical stimulation.^{39,40} The basic premise of EMG is that depolarization of a motor nerve produces a recordable electrical potential within one or more muscles innervated by that particular nerve. Electromyographic activity is recorded using intramuscular needle electrodes. Accurate interpretation of EMG is facilitated by simultaneous visual and auditory monitoring, so a speaker is used in parallel with a visual display to provide concurrent auditory feedback to the neurophysiologist and surgeon.

Spontaneous EMG is recorded throughout the course of surgery providing real-time feedback whenever a motor nerve is activated. Neurotonic EMG, characterized by irregular, high frequency (50–300 Hz) burst and train activity, is of greatest concern as it may be caused by nerve compression, traction, or blunt trauma.^{40,41} By contrast,

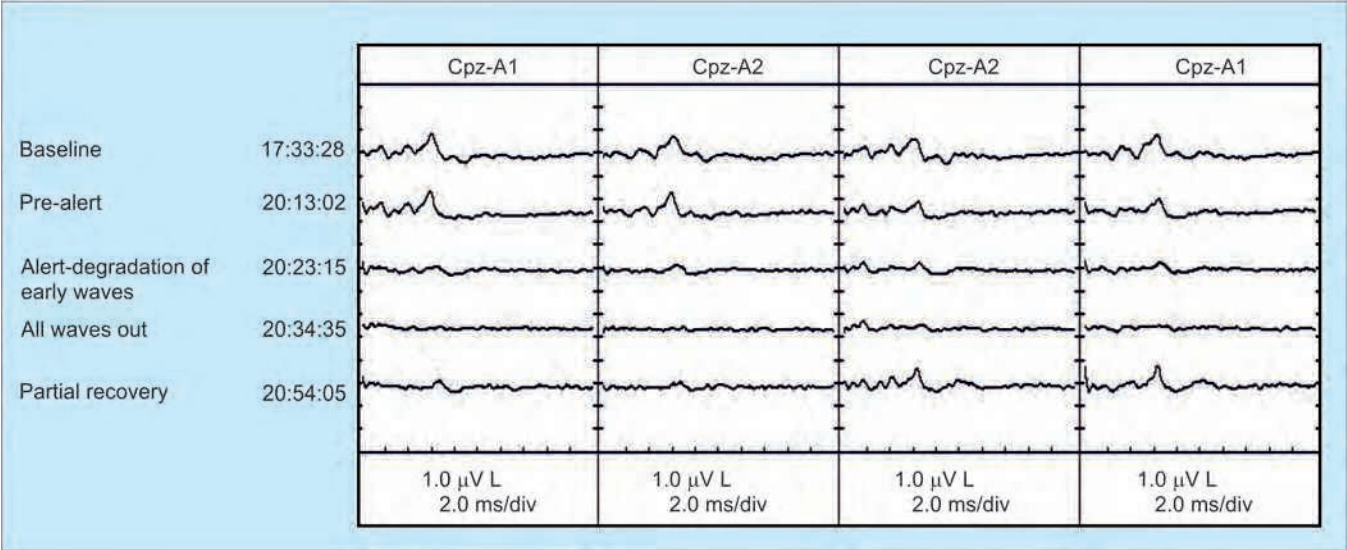


Fig. 12.2: Brainstem auditory evoked potential (BAEP) attenuation during posterior C1-3 instrumented fusion with lateral mass screw fixation for stabilization of an odontoid fracture, demonstrating sensitivity to brainstem infarct. Brainstem auditory evoked potentials were characterized by clearly formed waves I, III, and V, and bilaterally symmetrical I-V interpeak intervals just prior to placement of lateral mass screws (20:13). Following placement of screws (20:23), BAEPs exhibited marked bilateral amplitude attenuation, with no change in global EEG, transcranial electric motor evoked potentials, or somatosensory evoked potentials. Following a surgical pause, BAEPs began to show some signs of improvement. Subsequent postoperative studies revealed a posterior inferior cerebellar artery infarct. (Traces in the two columns on the left show BAEPs to stimulation of the left ear. Traces in the two columns on the right show BAEPs to stimulation of the right ear. Cpz, A1 and A2 designate recording electrode positions according to the International 10-20 System).

relatively regular, low frequency activity is usually benign and in some circumstances may indicate insufficient patient hypnosis.⁴¹

Electromyographic trains lasting longer than 10 seconds have been associated with postoperative deficit;⁴² however, absence of spontaneous EMG activity is not necessarily indicative of stable nerve function. Indeed, neurotonic EMG may be absent following serious nerve injury, including sharp dissection.^{43,44} Thus, spontaneous EMG has limited sensitivity to nerve injury.

Stimulus-triggered EMG is used in spine surgery to identify nerves, establish the functional integrity of nerves, rule out the presence of nerves within muscle or tumor mass, and to test for medial breach of pedicles following screw placement. A handheld probe is used to deliver electrical stimulation to the site of interest. When a nerve is depolarized, a response is recorded in the form of a compound muscle action potential (CMAP). The recording window is time locked to the onset of the stimulus, allowing the latency and amplitude of CMAPs to be quantified and compared. The *threshold*, operationally defined as the minimum current necessary to trigger a CMAP, can be used to gauge the functional status of the nerve that

is stimulated³⁹ and is also useful in differentiating neural versus non-neural tissue.⁴⁵

**BRAINSTEM AUDITORY
EVOKED POTENTIALS**

Brainstem auditory evoked potentials (BAEPs) are used to monitor vascular perfusion of the brainstem⁴⁶ and can be useful in high cervical spine surgery where there is increased risk for brainstem infarct secondary to vertebral artery injury.^{23,47} Auditory click stimuli are delivered to the ears through expandable foam ear buds inserted into the external auditory canal, and responses are recorded from electrodes placed near the ear/mastoid and vertex.⁴⁸ The BAEP consists of a waveform with five short-latency peaks that reflect neuronal activity in the ascending auditory pathway. The neural generators for the peaks are (I) distal auditory nerve, (II) proximal auditory nerve, (III) cochlear nucleus, (IV) superior olivary complex, and (V) lateral lemniscus or inferior colliculus.⁴⁹⁻⁵¹ A major ischemic accident secondary to vertebral artery compromise may result in disappearance of waves I-V.⁴⁶ When these changes do not resolve during the course of surgery, postoperative deficits may be expected.^{50,52} Figure 12.2 shows a BAEP

change during posterior C1-3 instrumented fusion with lateral mass screw fixation for a dens fracture.

■ OTHER NEUROMONITORING MODALITIES

In addition to the tests described above, there are a number of other monitoring modalities that can be of value during spine surgery. In particular, spinal cord function can be evaluated intraoperatively with tests that involve direct stimulation of and/or recording from spinal cord.³¹ These tests include spinal-cord-to-spinal-cord stimulation and recording,⁵³ spinal cord stimulation with peripheral nerve recording,⁵⁴ and spinal cord stimulation with muscle recording.⁵⁵

Spinal cord, spinal nerve root, and peripheral nerve functions can be evaluated with the use of intraoperative reflex tests. The H-reflex, for example, is a monosynaptic response that is recorded from muscle after electrical activation of an afferent nerve (e.g. gastrocnemius CMAP following posterior tibial nerve stimulation). The H-reflex has been used to monitor spinal cord, nerve root, plexus, and peripheral nerve function and has been used for research as a measure of the level of spinal cord excitability.⁵⁶ Similarly, the bulbocavernosus reflex (BCR) is a polysynaptic response recorded from the anal sphincter muscle following penile/clitoral electrical stimulation and has been used to monitor lower sacral nerve roots and the conus medullaris.⁵⁷ As with other tests, the relative merits of these modalities should be evaluated in the context of a multimodality approach to IONM.

■ IMPLEMENTING AND OPTIMIZING IONM

Proper execution of IONM requires extensive education and training on the part of the neuromonitoring team.¹ In addition to being technically skilled, the neurophysiologist in the operating room should be well versed in neuroanatomy, neurophysiology, neuropharmacology, and the relevant medical literature. Additionally, the neurophysiologist must possess strong communication skills and be familiar with the surgical procedure and anesthetic priorities. The success of IONM requires close, ongoing cooperation and communication between the IONM and anesthesia and surgical teams. It has been shown that hemodynamics, diabetes, and inhalational anesthetic technique are independent, but additive, factors that predic-

tably interfere with reliable recording of tceMEPs.⁵⁸ The effect of inhalational anesthetics on myogenic tceMEPs is particularly pronounced because these signals must overcome the effects of these agents on synaptic transmission in the spinal cord.³⁰ For these reasons, total intravenous anesthesia (TIVA) is oftentimes recommended to facilitate IONM, particularly when tceMEP monitoring is indicated.^{29,59,60}

The patient must also be sufficiently free of pharmacological blockade of the neuromuscular junction to allow both tceMEPs and EMG to be recorded with adequate sensitivity. A “train-of-four” test is sensitive to the number of bound nicotinic acetylcholine receptors and so provides an accurate, real-time assessment of the degree of neuromuscular blockade.⁶¹ Short acting neuromuscular blocking agents, administered to facilitate intubation and exposure, should be discontinued thereafter to facilitate sensitive tceMEP and EMG monitoring. The use of partial NMB has the potential for confounding interpretation of these signals because of difficulty maintaining a constant level of partial blockade, and because of the variable effects that partial blockade has on different muscle groups,⁶² particularly in patients with preexisting neurological dysfunction.⁶³

■ MECHANISMS OF INJURY AND REVIEW OF INTERVENTION STRATEGIES

The spinal cord and spinal nerve roots can be injured intraoperatively by a variety of primary mechanisms, including but not limited to compression, contusion, shear, distraction, laceration, ischemia, and thermal-related injury. As with all injury, a secondary biochemical process ensues. This secondary physiological reaction further exacerbates the primary injury and can include hemorrhage, vasospasm and loss of autoregulation, edema, axonal and neuronal necrosis, electrolyte imbalance, free radical production and lipid peroxidation, neurotransmitter accumulation, and apoptosis.⁶⁴⁻⁶⁶

While not all iatrogenic spinal cord injuries can be prevented or reversed, interventional strategies for evolving injuries endeavor to limit the extent and duration of injury. When IONM data are consistent with evolving spinal cord injury during surgery, the surgical team should be notified immediately. A surgical pause should be initiated, allowing the neurophysiologist to rule out all technical and anesthetic explanations for the IONM change, as well to avoid possible exacerbation of injury. Depending on

the proximate cause of neurophysiological change, the patient can be repositioned, spinal hardware and interbody graphs can be adjusted or explanted, distractive forces can be released, or irrigation can be applied to the neural elements in question. To address possible hypoperfusion of the spinal cord, mean arterial blood pressure should be elevated.²⁴ In some cases, intraoperative administration of steroids may be considered,⁶⁷ although this remains controversial.⁶⁸ As a prophylactic measure, close attention should be paid to maintenance of adequate blood pressure throughout the course of each spine procedure. This may require volume resuscitation using crystalloid, maintenance of a normal hematocrit, and administration of vasopressors.⁶⁵

IONM DURING CERVICAL SPINE SURGERY

Risk factors for neurophysiological deterioration during cervical spine surgery include preoperative myelopathy, long segmental extent of surgery, upper cervical surgery, use of instrumentation, and application of corrective forces to the neck.⁶⁹ Irrespective of whether cervical spine surgery employs an anterior or posterior approach, spinal cord function should always be monitored with both tceMEPs and SSEPs from both the upper and lower extremities. When the surgical manipulation poses risk to C5-C8 nerve roots, tceMEPs and free-running spontaneous EMG should be recorded from myotomes that are innervated by those roots.

Some pathologies of the cervical spine predispose the patient to elevated risk for neurological complications secondary to neck positioning. These include fracture/dislocation, cord compression, marked kyphosis, severe myelopathy, foraminal stenosis, ossification of the posterior longitudinal ligament, and space-occupying lesions. To the extent possible, a neutral neck position should be maintained during intubation and positioning. When the risk for injury is elevated, many anesthesia teams elect to perform an awake, fiberoptic intubation (AFI), which limits extension of the cervical spine while the airway is secured.^{70,71} The AFI also permits neurological assessment following intubation and sometimes final positioning.⁷² In the event that AFI is not available, or not possible, acquisition of postinduction, preintubation baseline tceMEPs is strongly recommended when the patient's pathology suggests elevated risk for extension injury. These responses form the basis for comparison with responses obtained following intubation. Appropriate neurophysiological monitoring

of the cervical spinal cord during this critical period requires significant preoperative planning, clear interpersonal communication, and a cooperative anesthesia team.

In addition to the risks associated with intubation, potential neurological complications secondary to patient positioning can be significant in cervical spine surgery. Destabilizing pathology of the cervical spine elevates the risk for new onset injury, particularly during prone positioning of the patient. Schwartz et al.⁷³ found that 1.8% of patients undergoing anterior cervical spine surgery had evidence of impending neurological injury. For many spinal procedures, surgical positioning can be critical. Positioning for surgery of the lower cervical spine and cervicothoracic junction can be particularly challenging with patients who have a large body habitus. Many times this can be addressed by applying countertraction to the shoulders in order to accommodate surgical exposure and lateral intraoperative radiography. However, a brachial plexus stretch or compression injury can sometimes occur from excessive countertraction. Also, circumferential tape around the arms can compress ulnar, median, or radial nerves. Somatosensory evoked potentials to stimulation of upper extremity peripheral nerves, as well as tceMEPs recorded from upper extremity myotomes, are particularly sensitive to impending peripheral nerve injury.^{73,74}

IONM DURING ANTERIOR CERVICAL SPINE SURGERY

Anterior cervical decompression and fusion (ACDF) surgery is one of the most commonly performed spine surgeries and is indicated for treatment of a wide range of pathology. A recent retrospective analysis of 1,015 patients revealed an overall morbidity rate of 19.3%.⁷⁵ In this study, the most common injuries were transient dysphagia (9.3%) and soft tissue hematoma (5.6%). Notably, 3.1% of patients exhibited clinical signs of recurrent laryngeal nerve (RLN) palsy, as evidenced by postoperative vocal cord paralysis. Therefore, ACDF surgery carries risk for RLN injury, particularly when the C7/T1 level is involved⁷⁶ and during reoperations.⁷⁷ While RLN monitoring with spontaneous EMG can provide valuable information about nerve irritation, absence of activity is not a reliable indicator of intact function.^{43,44} Complementing spontaneous EMG, stimulus-triggered EMG can be used to quickly, accurately, and safely identify the RLN and reduce the incidence of injury, allowing the surgeon to proceed with confidence.⁷⁸

Iatrogenic spinal cord or nerve root injury during ACDF surgery is rare, but can occur at a number of points during

the procedure. For example, spinal cord injury can occur as a result of vascular compromise or spinal cord stretch/traction during interbody distraction or graft placement and from spinal cord contusion or laceration during breach of the posterior longitudinal ligament or migration of a graft into the spinal canal. Likewise, nerve root injury can occur as a result of excessive traction during distraction, and contusion/laceration during foraminotomy or release of distraction. TceMEP testing, conducted after significant surgical maneuvers, provides the surgeon with timely warning of evolving injury. Attenuation or loss of all tceMEPs below the level at which the surgeon is working, with preservation of motor responses above that level is usually consistent with acute spinal cord trauma. Somatosensory evoked potentials from the upper and lower extremities can serve as an adjunct in determining the extent of injury to the spinal cord. Attenuation or loss of tceMEPs from a single myotome may indicate insult to a single nerve root.⁷⁹ Free-running EMG can be used as an adjunct to tceMEPs to identify nerve root compression or stretch. When tceMEP changes are not consistent with the level of surgery, the operating room team should investigate peripheral factors, such as positioning-related compression of the arm or hand.

Spine surgery at any segment carries risk for the development of an epidural hematoma, the onset of which may be delayed by some time.^{75,80} Attenuation of tceMEPs can also serve as an early indicator of developing epidural hematoma,⁸¹ giving the surgeon the opportunity to evacuate prior to the end of the procedure, and avoiding reoperation. Thus, it is recommended that the neurophysiologist continue monitoring at least through closure of fascia during cervical spine surgery.

IONM DURING POSTERIOR CERVICAL SPINE SURGERY

Posterior surgery of the cervical spine carries many of the same risks as those associated with anterior approaches, as well as several that are unique to the approach. Intraoperative neurophysiological monitoring changes during posterior laminectomy/laminotomy decompression of the cervical spine can be caused by a number of factors. In some cases, the dura can be particularly adhered to the lamina. Removing the adherent lamina can lead to the sudden release of the tethered dura, which may cause the spinal cord to recoil into the canal, producing acute traction or contusion of the cord. Decompressive laminectomy

of a severely stenotic canal indirectly decompresses the spinal cord allowing it to float away from compressive lesions, sometimes leading to temporary changes in spinal cord perfusion. This can cause biochemical changes to both the intracellular and extracellular environments, which result in transient conduction block.⁸² In this situation, tceMEPs and SSEPs may be abolished or attenuated for several minutes.

Posterior cervical fusion with pedicle and lateral mass screw fixation poses risk to the spinal cord and nerve roots and to the vertebral arteries.⁸³ When a breached screw comes in contact with neural elements, tceMEPs and, to a lesser extent, SSEPs can detect the insult if neural conduction has been altered. When pedicle screws are used, tceMEPs should be tested after each screw placement in order to increase specificity of injury detection. Pedicle screw placement in the cervical spine can be assessed with stimulus-triggered EMG. Djurasovic et al.⁸⁴ demonstrated that a 15 mA stimulus threshold had a sensitivity of 88% and a negative predictive value of 99% for correctly identifying a malpositioned pedicle screw. Additionally, stimulus-triggered EMG testing accurately identified 7 of 11 misplaced screws that were missed on plain radiographs.

Spinal cord tumors are typically treated from the posterior approach. It is not uncommon for tceMEPs and SSEPs to become attenuated or abolished during resection of intramedullary lesions, and additional spinal cord testing using D-wave recordings can provide valuable information that allows the surgeon to maximize tumor resection while preserving function. Following laminectomy, epidural D-wave recording electrodes should be placed both cephalad and caudad to the location of the tumor. A baseline D-wave should be established prior to opening of dura and must be established prior to performing a myelotomy. The D-wave is often robust over the cervical spine, owing to the abundance of corticospinal tract fibers, but may be impossible to record in the high cervical region because of contamination by stimulation artifact. Once the recording electrodes are secured, the surgeon must take great care not to move them during the course of surgery, because this can alter the waveform, potentially resulting in a false alarm.⁸⁵ Unlike myogenic tceMEPs, triggering of D-waves produces little or no patient movement, allowing for uninterrupted monitoring during the course of tumor resection.

The surgeon can take steps to decrease the severity of postoperative morbidity associated with myelotomy by

mapping the dorsal columns to identify the median raphe of the spinal cord and so provide a route of entry that is minimally disruptive. Change or even loss of SSEPs is common in intramedullary surgery and may occur immediately upon myelotomy.⁸⁶ Loss of myogenic tceMEPs should be reported, but the surgeon may proceed with resection in the face of an unchanged D-wave.³¹ Conversely, attenuation of the D-wave amplitude by >50% from baseline has been associated with long-term, if not permanent, motor deficit and warrants immediate surgical attention.^{12,87}

ADDITIONAL IONM CONSIDERATIONS DURING HIGH CERVICAL SPINE SURGERY

Anterior exposure of the high cervical spine (C1-3), whether transnasal, transoral, or through the anterior triangle of the neck, carries significant risk for cranial nerve neurapraxia or neurotmesis secondary to retraction or even blunt dissection through soft tissue.⁸⁸ Iatrogenic injury during high cervical surgery has been reported for the mandibular branch of the facial nerve,⁸⁹ the glossopharyngeal nerve,⁸⁸ the hypoglossal nerve,^{90,91} and the superior laryngeal nerve.⁹⁰ Whenever high anterior cervical spine surgery is planned, it is critical to have a preoperative discussion about potential risk to cranial nerves and the need to employ stimulus-triggered EMG for identification and preservation of cranial nerve function. TceMEP and EMG monitoring can be helpful during decompression of the foramen magnum for Chiari malformation, as well as during resection of intradural lesions, each of which may pose risk to the spinal accessory nerve (CN XI).

Instrumented fusion of the high posterior cervical spine places the brainstem at risk for ischemia secondary to vertebral artery injury (compression, rupture, or vasospasm). Brain stem auditory evoked potentials are sensitive to these changes. When the injury compromises blood flow to the brainstem/basilar artery watershed, waves I-V of the BAEP are abolished bilaterally.⁵⁰ Thus, BAEP testing has been recommended whenever screws are placed above the C3 vertebral level, or whenever there is elevated risk of brainstem ischemia secondary to vertebral artery injury.²³

IONM DURING POSTERIOR THORACIC SPINE SURGERY

The thoracic spine comprises the largest anatomic section of the spine, and the type of monitoring required to assess the neural elements depends on the pathology being treated and the planned surgical approach. The most com-

mon approach to the thoracic spine is from the posterior, and a variety of pathologies may be treated via this route. Iatrogenic neurological injury has been reported to the thoracic spinal cord, the conus medullaris, and spinal nerve roots during thoracic spine surgery.⁹² Lower extremity tceMEPs and SSEPs are used to monitor spinal cord long tract function during these procedures. If the conus medullaris is at risk, spontaneous and stimulated EMG can be used as adjunct modalities, providing additional, real-time information to the surgical team regarding the status of spinal nerve roots. Prepositioning baseline tceMEPs and SSEPs can be recorded for patients who are at increased risk of positioning-related spinal cord injury, including those with unstable spines due to fracture-dislocation, marked kyphotic deformities, myelopathy, or space occupying lesions. Monitoring brachial plexus and upper extremity peripheral nerve function is also of the utmost importance because surgical positioning of the limbs places them at risk during prone procedures.⁹³⁻⁹⁵

Intraoperative injury to the thoracic spinal cord can occur during laminectomy or other decompressive maneuvers, via the same mechanisms encountered during posterior cervical spine procedures. Mechanical injury also can occur secondary to placement of thoracic spinal instrumentation. Thoracic pedicle screws have gained popularity as components of spine constructs in recent years. Unlike hooks and wires, they do not require passage of instrumentation into the spinal canal. However, placing thoracic pedicle screws can be challenging, owing to the variable pedicle morphology and small pedicle diameters in the thoracic spine.⁹⁶ Transcranial electric motor evoked potentials are of value in detecting altered motor conduction in the event of inadvertent screw encroachment into the spinal canal and should be recorded following placement of each screw. The combined use of tceMEP and SSEP tests allows for real-time feedback regarding both motor and sensory conduction of the thoracic spinal cord.

While the practice of using stimulus-triggered EMG to test for medial breaches following placement of lumbar pedicle screws has gained acceptance, this methodology has not gained the same popularity in the thoracic spine. This is due, at least in part, to technical demands associated with obtaining artifact-free data, difficulty in isolating segmentally innervated musculature, and animal studies that highlight the challenges of interpreting results.^{97,98} While some have found value in this technique,^{99,100} consensus threshold criteria have not been established for detection of pedicle breaches.

Perhaps the most common application of IONM in thoracic spine surgery is its use during correction of

coronal or sagittal plane deformities within both the pediatric and adult populations. The inconsistent anatomy encountered in these populations makes the placement of pedicle screws challenging, particularly on the concave side of the deformity, which is more likely to approximate the spinal cord. Following coronal or sagittal correction of the spine, and finalization of instrumentation, multimodality monitoring should continue for a minimum of 20 minutes.^{101,102} Loss or attenuation of IONM signals secondary to vessel constriction and ischemia can develop over time, and the premature conclusion of monitoring could miss ischemic events leading to postoperative paraplegia. Timely elevation of blood pressure, adjustment of correction, or, in some cases, removal of hardware can be effective rescue interventions, as illustrated in Figure 12.1. While it is possible to insert epidural electrodes through a flavectomy to monitor D-waves during deformity correction, this may result in a high percentage of false positives, given that the corticospinal tracts can sometimes rotate away from the recording electrode.⁸⁵

Whereas osseous and epidural thoracic spinal tumors can be approached circumferentially, the approach to intradural and intramedullary tumors is usually from the posterior. Similar to surgery for degenerative processes or instability, the type of monitoring necessary for intradural lesions depends on their location, either cephalad to or approximating the conus medullaris. In addition to monitoring long tract conduction with tceMEPs and SSEPs when lesions approximate the conus medullaris, spontaneous and stimulus-triggered EMG can be used to distinguish neural from non-neural tissue. As in the cervical spine, the dorsal physiological midline can be mapped prior to myelotomy for intramedullary tumors.^{37,103} The D-wave is the gold standard for assessing descending motor conduction for intramedullary tumors; however, it is technically challenging to use this modality for lower thoracic or conus lesions. A sufficient percentage of corticospinal tract fibers must be present to generate this wave, and there must also be a sufficient amount of spinal cord caudal to the lesion to place the epidural recording lead.³¹

IONM DURING ANTERIOR THORACIC SPINE SURGERY

The anterior thoracic spine can be approached either via a sternotomy with the patient supine or via an anterolateral thoracotomy. The modalities monitored will again depend on whether the procedure is cephalad to the conus medullaris or approximating it. The lateral decubitus posi-

tion carries its own risks of peripheral neural compromise. In addition to upper extremity ulnar or median nerve monitoring, it can also be beneficial to monitor the radial nerves bilaterally, as they can be placed at risk for compression.¹⁰⁴ Additionally, care should be taken to pad the lower extremity and relieve pressure on the down side common peroneal nerve. Prophylactic padding or suspension of the fibular head is warranted, and monitoring of the distal peroneal nerve motor and sensory pathways can help to ensure ideal positioning without peripheral neural compromise.¹⁰⁵ With lateral positioning, oftentimes shifts in positioning can occur throughout the procedure that can lead to undue pressure on neurological structures in limbs, which are difficult to visualize due to surgical draping and the position of the patient. Intraoperative neurophysiological monitoring can be of great benefit in this situation providing early detection of evolving peripheral nerve injury.

Thoracic spine surgery in the lateral decubitus position often necessitates the sacrifice of one or more unilateral segmental arteries to gain access to the vertebral column. The T4 through T9 segments of the spinal cord comprise the critical vascular zone, where the cord is particularly vulnerable to ischemia.¹⁰⁶ The artery of Adamkiewicz, the largest of the segmental medullary feeder arteries, can also be encountered between T7 and L4 levels, with a bias for the left side of the cord.¹⁰⁶ There has been a debate as to the clinical significance of ligating segmental vessels during approaches to the thoracic spine, with some groups reporting on the relative safety of ligating multiple vessels^{107,108} and others publishing reports of intraoperative neuromonitoring signal changes and adverse postoperative neurological outcomes.^{109,110} Provocative testing can be carried out prior to ligation to help determine if the absence of particular vessels would elevate the risk of intramedullary ischemia. Segmental vessels may be temporarily occluded for several minutes while both tceMEPs and SSEPs are monitored to determine the effects of the occlusion on neural conduction. This may be particularly helpful in patients undergoing revision surgery, circumferential surgery, a left-sided approach, or those with kyphotic deformity who may be at an elevated risk for neural compromise secondary to a vascular etiology.¹⁰⁹

IONM DURING LUMBOSACRAL SPINE SURGERY

Although most surgeries in the lumbosacral spine do not place the spinal cord at direct risk of injury, IONM has seen increased application in these procedures to protect nerve root function. Depending on the pathology and the

surgical approach, spinal nerve roots can be placed at risk of injury within the thecal sac, as they exit the foramen, and peripherally as they form the lumbosacral plexus and peripheral nerves. There is no consensus on the most appropriate way to monitor these peripheral pathways, and the three “cornerstone” modalities all have their benefits and limitations. Electromyography is perhaps the most commonly utilized IONM modality in this region of the spine. The application of stimulus-triggered EMG as a means of testing medial pedicle cortex integrity following placement of pedicle screws is well established;^{18,111,112} however, the use of spontaneous EMG as a unimodal strategy can yield both high false-positive and high false-negative rates and has poor positive predictive value for adverse postoperative outcomes.⁴⁰

Lower extremity SSEPs are also limited in that they only survey the sensory aspects of the mixed peripheral nerves and the posterior spinal rootlets. Also, fibers from the peripheral nerves most commonly stimulated to elicit SSEPs enter the spine at several levels. Thus, injury to one of these roots may not sufficiently degrade the overall SSEP amplitude, resulting in a false-negative finding. Use of tceMEPs as a means of assessing individual lumbar nerve roots remains controversial due to radicular overlap, trial-by-trial variability, and lack of consensus on alert criteria and anesthetic regimens.²⁸ Despite these limitations, tceMEPs can be a useful component of a multimodality monitoring plan.^{113,114} The potential utility of tceMEPs as an adjunct modality when monitoring in the lumbosacral spine has been shown in a porcine model,^{115,116} and a retrospective intraoperative study,¹¹⁷ which demonstrate the ability of tceMEPs to detect isolated nerve root injury.

IONM DURING POSTERIOR LUMBOSACRAL SPINE SURGERY

As with the thoracic spine, the most common approach to the lumbar spine is from the posterior. Monitoring of the upper extremities, either by SSEPs or tceMEPs, can help to detect impending compression or stretch of the brachial plexus or the peripheral nerves.⁹³ Prepositioning data should be obtained in the face of either an unstable spine or preexisting brachial plexopathy. Iatrogenic injury may occur secondary to decompression, osteotomy, correction of deformity, unintended durotomy, retraction of a nerve root or the thecal sac, placement of instrumentation, place-

ment of interbody graft, tumor resection, or cord untethering.

Recording of triggered EMG to electrical stimulation of pedicle screws has been used successfully for more than two decades to assess the integrity of the medial pedicle wall.^{18,111,118} This threshold technique allows for effective detection of medially malpositioned screws, while limiting the amount of intraoperative and postoperative radiation exposure that would occur with intraoperative O-arm or postoperative CT scan, respectively.¹¹⁹ A limitation of triggered EMG is that it is lacking in ability to detect lateral breaches in pedicle integrity. It is important to note that abnormally high stimulation thresholds may be encountered in the face of chronically compressed nerve roots, or preexisting comorbidities such as neuropathy or myopathy,³⁹ possibly leading to false-negative results. In these situations, nerve roots can be exposed and directly stimulated, thereby establishing a control threshold against which thresholds to screw stimulation can be compared.¹¹¹ High thresholds can also be caused by current shunting through fluid in the surgical field or a retractor in contact with the screw head, drawing current away from the intended pathway, and producing a false-negative result. Meticulous stimulating techniques are always necessary to ensure the accuracy of test results.

Lumbar deformity correction places the spinal nerve roots at an increased risk compared with surgery for degenerative conditions. Iatrogenic injury can occur during screw placement, pedicle subtraction, or correction of kyphosis. Reduction of high-grade spondylolisthesis may subject the spinal nerve roots to stretch, thereby increasing the likelihood of postoperative deficit.^{120,121} Fixed sagittal imbalance can be addressed in the lumbar spine through single or multilevel osteotomy with instrumented correction of kyphosis. Sagittal correction may place neural elements at risk at multiple points, as the spinal cord, spinal nerve roots, and peripheral nerves are all susceptible to stretch with reintroduction of lordosis into the vertebral column. Lieberman et al.¹¹⁷ demonstrated successful identification of lumbar spinal nerve root injury with tceMEPs during correction of fixed sagittal plane deformities, using an alert criterion of >80% amplitude decrease.

Multimodality IONM is also useful in protecting neural function during resection of cauda equina lesions and spinal cord untethering in the dysraphic population.¹¹⁴ Stimulus-triggered EMG is the gold standard for mapping in these procedures, allowing for differentiation of neural from non-neural tissue, as well as sensory from motor fibers.

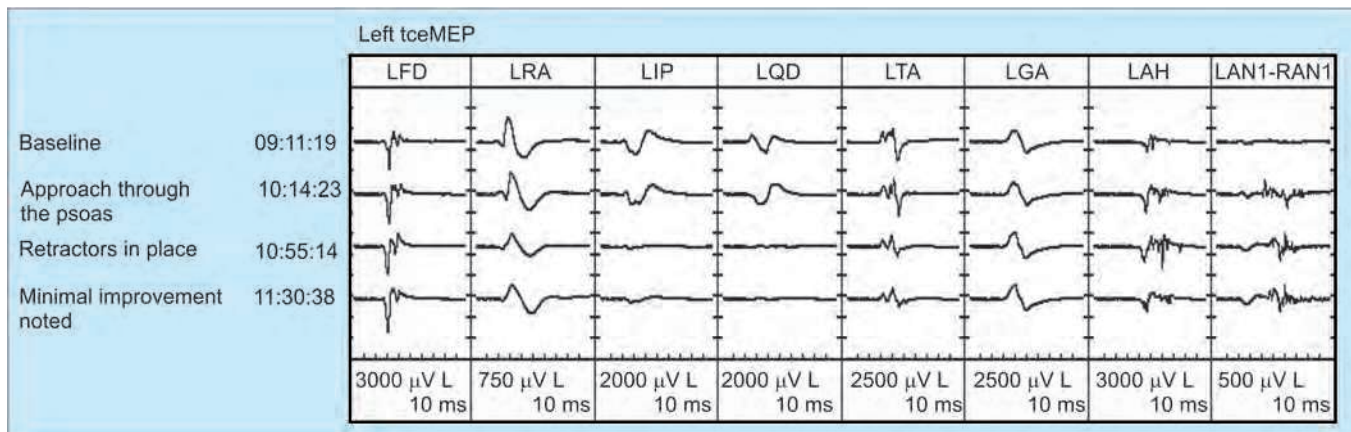


Fig. 12.3: Transcranial electric motor evoked potential (tceMEP) attenuation during anterolateral transpsoas L3/4 discectomy with interbody fusion for pseudoarthrosis, demonstrating sensitivity to evolving peripheral nerve injury. Transcranial electric motor evoked potentials were of sufficient size and consistency for reliable monitoring at baseline and during the approach through the muscle. Following placement of the retractor, there was a loss of the left-side tceMEPs from iliopsoas and quadriceps myotomes. There was no remarkable spontaneous or stimulus-triggered electromyographic activity during the approach or following retractor placement. Despite removal of the retractors, there was only minimal improvement during the balance of the procedure. Postoperatively, the patient presented with new onset left femoral nerve palsy. (FD: First dorsal interosseous; RA: Rectus abdominis; IP: Iliopsoas; QD: Quadriceps; TA: Tibialis anterior; GA: Gastrocnemius; AH: Abductor hallucis; AN: External anal sphincter; Prefixes L and R indicate the left and right sides, respectively).

IONM DURING ANTERIOR LUMBOSACRAL SPINE SURGERY

Anterior and anterolateral approaches to the lumbar and lumbosacral spine have become increasingly popular in recent years. However, the anterior approach carries its own unique risks, in addition to those described for the posterior approach. Ischemic events can occur secondary to retraction of the aorta, vena cava, or iliac vessels to gain access to the correct spinal levels.¹²² Pulse oximetry of the lower extremities is commonly used to help detect evolving infarction. Lower extremity SSEPs and tceMEPs are also sensitive to ischemia and can serve as an adjunct to pulse oximetry and use of vital signs.^{123,124} Injury to the superior hypogastric plexus can result in sexual dysfunction and retrograde ejaculation in the male population. At present, reliable intraoperative detection of injury to the autonomic nervous system remains a significant monitoring challenge.

The anterolateral, transpsoas approach to the lumbar spine has gained popularity in recent years as an alternative to the supine retroperitoneal approach. The transpsoas approach has the benefit of reducing risk of injury to major vasculature; however, it places the exiting nerve roots and the lumbosacral plexus directly at risk as they pass through the psoas muscle.¹²⁵ In a recent review of the literature and parallel case series, Sofianos and colleagues¹²⁶ reported

a variable rate of complication associated with the transpsoas approach to the spine, with their own series yielding a 40% complication rate. As the psoas muscle is traversed, stimulus-triggered and spontaneous EMG can be used to assess the proximity of dilators and other instruments to neural elements. In addition, tceMEPs can provide valuable information about evolving stretch injury outside the exposed field that might otherwise be missed, as illustrated in Figure 12.3. Likewise, injury to the contralateral nerve roots occurring secondary to discectomy or graft placement may not be detected with EMG alone, pointing to the need for a multimodality monitoring approach during these procedures.¹²⁷

CONCLUSION

Over the past decades, the evolution of IONM has seen it advancing from humble laboratory beginnings as a single test to a comprehensive continuous multimodality strategic analysis of the nervous system. This has made it an invaluable asset in the advancement of the field of spine surgery as a whole, providing monitoring with broad-based coverage of at-risk neural elements. Large prospective, blinded studies of IONM efficacy are lacking in the literature and may never be performed given ethical considerations. There is, however, a growing body of literature pointing to the effectiveness of neuromonitoring in detection of intraoperative neural injury.¹²⁸ Most IONM studies

provide class II or class III evidence of efficacy, which is also true for much of the current practice in neurosurgery.¹²⁹ Timely detection is a key factor in identifying proximate causes of evolving injury, providing effective intervention, and mitigating neurological sequelae. The high sensitivity and specificity of IONM using a multimodality approach have proven its efficacy over the past decades and in many instances have made the need for tests such as the Stagnara wake-up test obsolete. Moving forward, evidence for the utility of IONM will be based on good clinical outcomes, historical controlled studies, and cost-benefit evaluations.¹²⁹ As the spectrum of spine surgery continues to progress into areas such as tumor, trauma, and minimal access surgery, the role of IONM will undoubtedly continue to be integral and invaluable in the care of patients.

KEY POINTS

- The primary goal of IONM is prevention of postoperative neurological sequelae through early intraoperative detection of evolving injury and timely intervention.
- Intraoperative neurophysiological monitoring is based on the premise that neurophysiological activity changes in a measurable and reversible way before the onset of permanent neurological deficit, opening a window of opportunity for correction.
- Intraoperative neurophysiological monitoring carried out by a skilled neurophysiologist is effective in detecting intraoperative neural injury.
- A multimodality IONM strategy, based on careful preoperative assessment of patient and procedure-specific risk factors, is required for comprehensive neurophysiological surveillance during spine surgery.
- Multimodality IONM has found increased application during spine procedures in recent years, both for monitoring functional neural integrity and mapping neural tissue.

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The authors recommend evidence-based approaches to minimize the chance of perioperative spinal cord injury and to optimize outcome in the event of an injury. A systematic review of the literature focuses on the pathophysiology of spinal cord injury, and options for prevention and treatment are outlined.

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Stimulus-triggered EMG has been well recognized for improving both the accuracy and safety of pedicle screw implantation. The authors thoroughly reviewed historical events, IONM modalities, alarm criteria, clinical efficacy, current trends, and caveats related to pedicle screw stimulation along the entire vertebral column.

- Nuwer MR, Emerson RG, Galloway G, et al. Evidence-based guideline update: intraoperative spinal monitoring with somatosensory and transcranial electrical motor evoked potentials. *J Clin Neurophysiol*. 2012;29(1):101-8.

The authors review class I and II studies to evaluate whether IONM with SSEPs and/or tceMEPs predicts adverse surgical outcomes. All studies reported that paraparesis, paraplegia, and quadriplegia occurred in the face of evoked potential (EP) changes, with no occurrences in the absence of EP changes. The authors state that IONM is established as effective to predict an increased risk of adverse outcomes in spinal surgery and conclude that members of the operating team should be alerted to these risks in patients with important IONM changes.

Anesthesia and Perioperative Care of Patients for Spine Surgery

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Snapshot

- » Preoperative Evaluation and Optimization of the Patient for Elective Spine Surgery

INTRODUCTION

Surgery on the spine encompasses a broad spectrum of elective and emergency procedures with vastly different considerations. Spine surgery procedures may be performed in a day surgery setting or they may involve complex, staged operations performed over multiple days with the attendant fluid shifts, blood loss, and potential for multi-organ dysfunction. Preoperative identification and optimization of comorbidities coupled with appropriate management throughout the perioperative period is paramount for patients undergoing spine surgery. In this chapter an anesthesiologist's approach to perioperative evaluation, optimization, and management of the spine surgery patient is presented. In addition, the management of medical complications of spinal cord injury (SCI), bleeding and clotting complications, options for pain management, and managing complications uniquely associated with spine surgery are discussed.

PREOPERATIVE EVALUATION AND OPTIMIZATION OF THE PATIENT FOR ELECTIVE SPINE SURGERY

Cardiovascular System

Cardiovascular complications are among the most common following surgery and are associated with significant morbidity and mortality.¹ The American College of Cardiology/American Heart Association (ACC/AHA) published

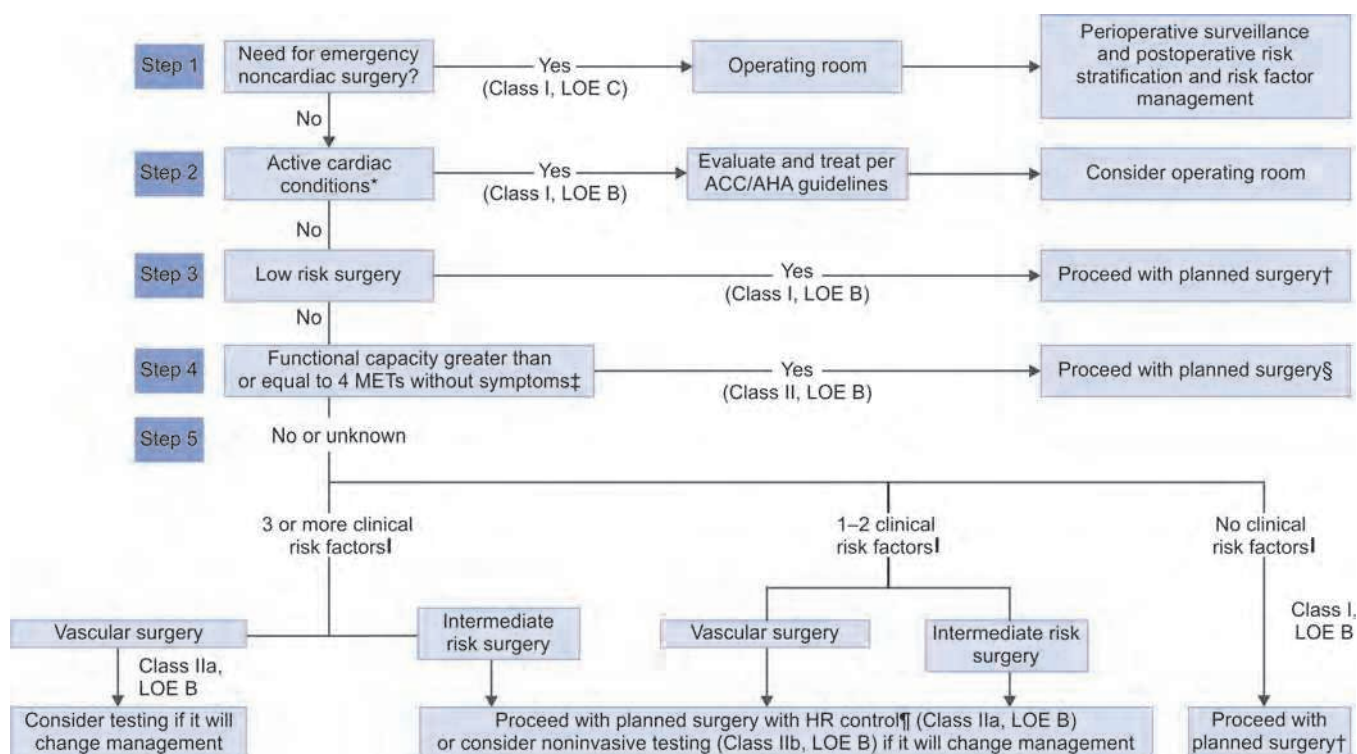
guidelines on perioperative cardiovascular evaluation and care for patients undergoing noncardiac surgery to help reduce perioperative morbidity and mortality from cardiovascular events.²

The AHA/ACC guidelines follow a stepwise and algorithmic approach that begins with determining the urgency of surgery (Flowchart 13.1). Patients who require emergency surgery should proceed to the operating room with baseline investigations and optimization performed as time and the patient's condition allow (class 1, level of evidence: C). Intraoperative management may be modified, and further surveillance and management of cardiovascular disorders is undertaken after surgery.

When surgery is not emergent, patients are evaluated for "active" cardiac conditions: unstable coronary syndromes, decompensated heart failure, significant dysrhythmias, or severe valvular disease. The benefit of optimizing these conditions should be considered against the risk of delaying surgery. Patients with active cardiac conditions should undergo evaluation and possibly treatment before noncardiac surgery (class I, level of evidence: B). Appropriate management of an active condition is required regardless of the need for surgery. An important caveat is that decisions to offer interventions (such as revascularization in patients with coronary artery disease) are made independent of the imminent proposed surgery.

Most spine surgery is considered intermediate risk with expected adverse cardiac event rates of 1–5% (cardiac death and nonfatal myocardial infarction). For intermediate risk surgery, functional capacity and patient risk

Flowchart 13.1: Cardiac evaluation and care algorithm for noncardiac surgery based on active clinical conditions, known cardiovascular disease, or cardiac risk factors for patients 50 years of age or greater.



(ACC/AHA: The American College of Cardiology/American Heart Association; LOE: Level of Evidence; METs: Metabolic equivalent tasks).

* Active cardiac conditions: Unstable coronary syndromes, decompensated heart failure, significant arrhythmias, and severe valvular heart disease.

† Noninvasive testing is not useful for patients with no clinical risk factors undergoing intermediate-risk and low-risk noncardiac surgery. (Level of Evidence: C)

‡ 4 METs (metabolic equivalent task) includes the ability to climb a flight of stairs or walk up a hill

§ Noninvasive testing may be considered before surgery in specific patients with risk factors if it will change management.

I Clinical risk factors include ischemic heart disease, compensated or prior heart failure, diabetes mellitus, renal insufficiency, and cerebrovascular disease.

¶ If the patient has 1 or 2 clinical risk factors, then it is reasonable to either proceed with the planned surgery, with heart rate control with beta blockade (controversial), or consider testing if it will change management.

Source: Fleisher LA, Beckman JA, Brown KA, et al. ACC/AHA 2007 guidelines on perioperative cardiovascular evaluation and care for noncardiac surgery: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Writing Committee to Revise the 2002 Guideline.) *Circulation*. 2007;116:e418-99.

factors determine need for further investigations. Functional capacity is often described in terms of metabolic equivalent tasks (METs): one MET is oxygen required for basal metabolic function. Patients who can complete four METs (climbing a flight of stairs or walking up a hill) without symptoms can proceed to surgery (class IIa, level of evidence: B). Functional assessment is often limited as many patients for spinal surgery cannot exercise due to pain or disability from their spinal condition. The Revised Cardiac Risk Index (RCRI) identifies five independent risk correlates (besides high-risk surgery): stable ischemic heart disease, controlled or prior congestive heart failure, cerebro-

vascular disease (history of stroke or transient ischemic attack), insulin-requiring diabetes, and renal insufficiency.³ Patients with poor functional capacity or who are limited by pain or disability to less than four METs and who have RCRI risk factors should be investigated further if this will change the perioperative management of the patient (class IIb, level of evidence: B). Options for noninvasive testing for coronary artery disease in patients who are unable to exercise include radionuclide myocardial perfusion imaging and dobutamine stress echocardiography, the latter having slightly better diagnostic performance.⁴

Antiplatelet Agents

Aspirin, also known as acetylsalicylic acid (ASA) and clopidogrel are used for primary and secondary prevention of patients with cardiovascular disease (including those with coronary stents). Historically, these drugs are discontinued 7 days or more before surgery due to concerns about risk of perioperative bleeding. Recently this practice has been questioned as it may increase the risk of postoperative cardiovascular morbidity and mortality.⁵

In a retrospective review of 244 patients undergoing spinal instrumentation and fusion, there was no increase in bleeding or transfusion in patients taking ASA.⁶ In their review of perioperative antiplatelet therapy, Chassot et al. acknowledge that while prospective studies with high degree of evidence are lacking, the increased bleeding risk associated with continuing ASA throughout the perioperative period may be outweighed by the greater risk of coronary thrombosis with significant morbidity and mortality.⁷ Although surgery in an enclosed space such as intracranial neurosurgery or intramedullary canal surgery could be considered an exception, Chassot contends that ASA should never be stopped when prescribed for secondary prevention of cerebrovascular and cardiovascular conditions. When ASA is used as primary prevention, it may be withdrawn but no more than 7 days before surgery. Elective surgery may be inadvisable in patients on clopidogrel or dual therapy, and direction from hematology or cardiology is required. Antiplatelet agents should be resumed as soon as possible after surgery when the risk of postoperative bleeding has diminished.⁸

Intraoperative Management of Patients at Risk for Cardiovascular Complications

Patients at risk for cardiovascular complications may require more intensive ischemia and blood pressure monitoring, have a lower tolerance for blood pressure and heart rate fluctuations, and require a higher transfusion threshold.^{2,9} The decision to include arterial and central venous monitoring is based on patient comorbidities and surgical factors such as extent of cardiovascular disease, duration of surgery, potential need for vasoactive drugs, and an anticipation of significant blood loss. Noninvasive cardiac output monitors may be considered to help guide fluid resuscitation and use of vasoactive drugs.^{10,11} Postoperative surveillance in susceptible patients is critical for early recognition and management of ischemia.²

Cardiovascular Management in Spinal Cord Injury

Management of the cardiovascular complications of the patient with acute SCI requires knowledge of the pathophysiology of this condition. The goal when resuscitating a patient with SCI is to prevent secondary injury by ensuring adequate oxygen delivery to the spinal cord. Hypotension following SCI is common, although various definitions for hypotension have been used. In an observational study by Levi and colleagues, systolic blood pressure (SBP) <90 mm Hg on admission was present in 8 of 50 (16%) of patients admitted with SCI. This proportion was higher in patients presenting with quadriplegia (7 of 31, 26%).¹² Another observational cohort of patients admitted with isolated complete SCI demonstrated a progressive increased proportion of patients with hypotension with a more cephalad injury. In this cohort, SBP <100 mm Hg occurred in 70 of 301 (26%) of complete cervical SCI, compared with 16 of 155 (12%) with thoracic and 1 of 34 (3%) with complete lumbar injuries, respectively.¹³ Patients with SCI are predisposed to hypotension from multiple causes including neurogenic shock, hypovolemia from hemorrhage, and obstructive or cardiogenic shock from major cardiothoracic trauma.

The mechanisms behind neurogenic shock are well characterized.¹⁴ Damage to the autonomic nervous system in SCI causes decreased sympathetic outflow leading to decreased vasomotor tone and reduction in systemic vascular resistance. Spinal cord injury at T6 results in decreased outflow from the sympathetically mediated cardiac accelerator fibers causing a decrease in heart rate and decrease in contractility. Parasympathetic innervation to the heart remains intact resulting in imbalance, severe bradycardia, and decreased contractility. Long-term autonomic dysfunction from severe SCI leads to orthostatic hypotension and autonomic dysreflexia.¹⁴

The American Association of Neurological Surgeons/Congress of Neurological Surgeons recommend that a mean arterial pressure of 85–90 mm Hg be maintained for the first 7 days following acute SCI.¹⁵ Clinical practice guideline from the Consortium for Spinal Cord Medicine also recommends prevention and treatment of hypotension using fluids and vasopressors to maintain an MAP of 85 mm Hg for 7 days.¹⁶ The clinical evidence supporting this recommendation is weak, consisting of uncontrolled observational studies.^{12,17} In patients suffering from traumatic brain injury (TBI), SBP <90 mm Hg has been consistently associated with worse long-term outcomes,¹⁸

and therefore maintenance of cerebral perfusion pressure has become a cornerstone in the critical care management of TBI.¹⁹ Given this intervention is reasonably well tolerated, combined with strong biologic rationale, it seems prudent to maintain spinal cord perfusion using MAP goals recommended above. Adequate volume repletion with appropriate fluids, titrated vasopressor therapy with either norepinephrine or dopamine (the latter in patients with bradycardia), and early arterial pressure monitoring and central venous access are crucial to optimize spinal cord perfusion in acute SCI.

Respiratory System

As with cardiovascular system risk assessment, determination of risk for postoperative pulmonary complications (PPCs) guides perioperative management and may reduce complications.^{20,21} Optimization of respiratory conditions requires identification of modifiable risk factors and provision of appropriate treatment, which is usually indicated regardless of the need for surgery. Both surgical and patient factors impact perioperative pulmonary risk assessment.

The incidence of PPCs is high, and PPCs are associated with perioperative morbidity and mortality. Pulmonary complications may be the most important factors increasing hospital stay and costs.^{22,23} Pulmonary complications include atelectasis, bronchitis and pneumonia, bronchospasm, and exacerbation of underlying lung disease as well as respiratory failure.²⁴ In a multivariable cohort analysis, Lee et al. found PPCs to be independently associated with death within 2 years in patients undergoing lumbar spine surgery.²⁵ Using the American College of Surgeons National Surgical Quality Improvement Program data set, Gupta et al. demonstrated the risk of postoperative respiratory failure (failure to wean from mechanical ventilation within 48 hours of surgery or unplanned intubation/reintubation postoperatively) occurred in 3.1% of patients undergoing a variety of procedures in both community and academic centers.²⁶ Twenty-five percent of patients with postoperative respiratory failure died within 30 days.

The American College of Physicians guidelines identify patient-specific risk factors for PPCs: chronic obstructive pulmonary disease (COPD), advanced age, American Society of Anesthesiologists classification of 2 or higher, functional dependence, and congestive heart failure.²⁷ In a prospective multicenter cohort study, Canet et al. also demonstrated that a low preoperative arterial oxygen saturation, acute respiratory infection during the previous month,

and preoperative anemia to be risk factors for PPCs.²⁸ Additional patient factors include smoking, obesity, obstructive sleep apnea (OSA), and pulmonary hypertension.²⁹ Emergency procedures, prolonged surgery (>3 hours), and operations proximate to the diaphragm increase the risk of PPCs.³⁰ In their analysis of medical complications following lumbar spine surgery, Lee et al. found the invasiveness of the procedure to be one of the highest predictors.²⁵

Tobacco smoking is a consistent risk factor for perioperative respiratory, cardiovascular, and wound healing complications following surgery.^{31,32} Smoking cessation is of particular importance for successful spine fusion surgery,³³⁻³⁵ and some centers performing spine fusion measure urine nicotine levels preoperatively and decline patients who continue to smoke.³⁶ Major surgery may be an opportunity to facilitate smoking cessation.³¹ However, despite effective interventions,³⁷ clinicians do not consistently counsel patients on the importance of smoking cessation.³²

Chronic obstructive pulmonary disease is a common and important risk factor associated with perioperative respiratory complications.³⁸ Elective surgery should be postponed during an exacerbation of COPD, and treatment with antibiotics and steroids instituted to achieve the best possible level of pulmonary function preoperatively. Perioperative administration of inhaled beta agonists and anticholinergics are indicated in patients responsive to their bronchodilating effects.²¹ Patients with well-controlled asthma seem to have no increased complication rates associated with surgery,³⁹ although severe bronchospasm may occur associated with general anesthesia where asthma is poorly controlled.⁴⁰

Obstructive sleep apnea is associated with increased PPC and potential difficult airway management.⁴¹ The American Society of Anesthesiologists recommends preoperative surveillance for OSA to identify patients and initiate continuous positive airway pressure (CPAP) therapy before surgery in severe cases.⁴² Postoperative management of OSA includes resuming CPAP early, careful titration of respiratory depressant medications, and appropriate monitoring during recovery from surgery.

Deep breathing and cough, incentive spirometry, intermittent positive pressure breathing, and CPAP are effective in preventing PPCs.⁴³⁻⁴⁵ Patient effort is critical in these lung expansion techniques, which are best taught prior to surgery, and appropriate analgesia facilitates postoperative respiratory therapy. Preoperative inspiratory muscle training reduces PPC in patients having cardiac and abdominal surgery.^{46,47} Intraoperative measures to reduce PPC

include intubating with modified endotracheal tubes in patients expected to require mechanical ventilation after surgery. These tubes allow subglottic secretion drainage and reduce the incidence of ventilator-associated pneumonia.⁴⁸⁻⁵⁰ Low tidal volume (6–8 mL/kg) ventilation may be associated with improved clinical outcome even in patients without adult respiratory distress syndrome.⁵¹ Intraoperative placement of postpyloric feeding tubes where prolonged postoperative intubation is possible or where swallowing is predicted to be impaired such as following anterior cervical surgery may protect from aspiration and allow early feeding.⁵²

Respiratory Management in SCI

Respiratory failure necessitating intubation and ventilation is common following acute cervical SCI especially in patients with complete cervical injuries⁵³ and injuries at the C5 level or above^{54,55} in whom phrenic nerve and diaphragmatic dysfunction lead to reduced tidal volumes and vital capacity.⁵⁶ Observational studies show that intubation will be required in 69–88% of patients with SCI at C5 or above.^{57,58} While diaphragmatic function is preserved in lower cervical spine injuries, intercostal muscle paralysis results in chest wall indrawing during inspiration and ventilatory dysfunction.⁵⁶ Impaired cough from abdominal muscle paralysis reduces clearance of secretions leading to mucous plugging and increased risk of pneumonia.

The decision to intubate is often based on multiple factors and requires judgment of the clinician. These patients require monitoring in a high acuity environment and, although no firm intubation criteria exist, it should be considered when signs of fatigue become apparent. Vital capacity can be followed over time and intubation considered once vital capacity becomes <15 cc/kg.⁵⁹ Airway instrumentation may lead to secondary SCI as intubation can result in cervical spine movement. Although direct laryngoscopy results in movement of the cervical spine,⁶⁰ when combined with manual in-line stabilization it remains a reasonable option, particularly in patients who are either uncooperative or require immediate intubation. Survey data demonstrate that anesthesiologists prefer to use a spontaneous breathing technique with fiberoptic bronchoscopy.⁶¹ This technique has several advantages: the neck is maintained in neutral position minimizing spine movement with excellent glottic visualization, and a neurologic examination following intubation assures no secondary damage has occurred.

The majority of patients with cervical SCI will liberate from mechanical ventilation provided diaphragmatic function remains intact. Tracheostomy may be used to facilitate liberation and has several advantages including decreased airway resistance, thereby reducing respiratory work and greater patient comfort than endotracheal intubation. Tracheostomy may reduce the risk hospital-acquired pneumonia⁶² and reduce days free of ventilation and intensive care.⁶³

Renal Management

Perioperative renal management centers on preserving function and preventing injury. The incidence of perioperative acute kidney injury (AKI) in spine surgery is unknown. In a prospective observational study, risk factors for AKI in noncardiac surgery patients with normal preoperative renal function were age, emergent surgery, liver disease, body mass index, high-risk surgery, peripheral vascular occlusive disease, and COPD requiring chronic bronchodilator therapy.⁶⁴ In the same study, intraoperative total vasopressor dose, use of vasopressor infusion, and diuretic administration were independent predictors of renal failure, which occurred in 0.8% of patients. In patients undergoing major surgery, Abelha et al. found similar predictors for AKI as well as American Society of Anesthesiologists physical status, coronary artery disease, and RCRI score in patients with previously normal renal function who required intensive care following surgery.⁶⁵

Although no specific interventions have been shown to prevent AKI, maintaining renal perfusion is paramount given association of AKI with hypotension, diuretic use, and bleeding requiring transfusion.⁶⁶ Avoiding angiotensin-converting enzyme inhibitors and angiotensin II receptor antagonists prior to surgery may be advisable, especially when hypotension is anticipated.⁶⁷ Other elements of perioperative care may affect AKI such as use of synthetic colloids, which increase the risk of AKI in lung resection surgery⁶⁸ and patients with sepsis.⁶⁹

Blood and Coagulation Management

Risks of blood product transfusion include acute hemolytic reaction, transfusion-related acute lung injury, bacterial and viral infections, and transfusion-related immunomodulation. Transfusion-related immunomodulation is associated with increased postoperative infection,⁷⁰ length of hospital stay, and possibly cancer recurrence.⁷¹ The decision to transfuse must be weighed against the risks of anemia and coagulopathy.

Preoperative anemia is common; one Canadian institution found an incidence of 40% in elective surgical patients.⁷² In this study, anemia was an independent predictor of 90-day mortality, and anemic patients were more likely to require transfusion. Many hospitals now have blood management programs that target patients having surgery with high transfusion rates, such as major spine surgery. These programs identify, optimize, and treat patients with preoperative anemia and further make recommendations on intraoperative red blood cell conservation. Patients are ideally referred to the program when first assessed for surgery, allowing adequate time for management. Options for preoperative management include iron supplementation, erythropoietin, and autologous donation. Intraoperative recommendations may include use of antifibrinolytics, cell salvage, and acute normovolemic hemodilution (ANH).

Preoperative Management

Iron replacement is recommended when deficiency exists. Oral iron replacement may be sufficient if there is adequate preoperative time prior to surgery (>2 months). In cases where there is insufficient time prior to surgery, poor response to oral iron, and cases of intolerance to oral Fe, parenteral Fe is recommended. Erythropoietin may be used, particularly in patients who refuse blood products, where there has been an inadequate response to iron therapy and to improve hemoglobin recovery in patients donating autologous blood.

Preoperative autologous blood donation may be offered to patients wishing to avoid allogeneic blood. One to three units of blood can be drawn preoperatively at 1-week intervals and returned during surgery. Risks of autologous blood include clerical error and bacterial infection. The transfusion trigger should be the same as for allogeneic blood, and collected units may thus be discarded. Patients may have inadequate recovery of hemoglobin, resulting in preoperative anemia and blood may outdate should the operative date be postponed.⁷³

Intraoperative Management

Antifibrinolytic medications (tranexamic acid and epsilon-aminocaproic acid) block the activation of plasminogen to plasmin and are routinely used in major spine surgery.^{74,75} The fibrinolytic system is activated during surgery, resulting in breakdown of preexisting clot and secondary bleeding.

Cell salvage is the most effective blood-saving technique available.⁷⁶ Shed blood is aspirated from the wound, mixed with anticoagulant and filtered into a reservoir, washed, and returned to the patient. Red blood cells obtained from cell salvage are free from platelets and clotting factors, which are removed during the process. This can lead to dilutional coagulopathy. Limiting suction pressures, turbulent flow in the field, and allowing blood to pool as much as possible before collection will minimize damage of red cells and maximize recovery. The majority of patients refusing red cell transfusion will accept cell salvage. Cell salvage has been considered contraindicated in cases of infection or cancer, although the concern of cancer spread has recently been questioned, particularly with the use of leukocyte reduction filters.⁷⁷

Acute normovolemic hemodilution involves blood collection in the operation room prior to blood loss and subsequent volume replacement with crystalloids or colloid. Because fresh whole blood obtained through ANH contains platelets and clotting factors, the risk of dilutional coagulopathy is mitigated, although the clinical benefits of ANH remain unclear.⁷⁸ The majority of patients refusing blood products will accept ANH.

Intraoperative management of volume status involves ongoing assessment of blood loss, laboratory testing, and appropriate fluid management including transfusion when necessary. When blood loss is significant, serial hemoglobin and coagulation parameters are measured. Transfusion trigger for red cells is generally considered to be between 60 and 80 g/L with a higher trigger in patients with ischemic heart disease and when blood loss is large and ongoing.⁹ Cryoprecipitate may be used when fibrinogen is low despite administration of plasma. Activated Factor VIIa is considered in rare circumstances of microvascular bleeding despite replacement of clotting factors,⁷⁹ and fibrinogen concentrates may also show promise in this situation.⁸⁰

Venous Thromboembolism Prophylaxis

Venous thromboembolism (VTE) is a common and preventable cause of death in hospital.⁸¹ There are approximately 200,000 deaths related to VTE per year in the United States with trauma and the postoperative period being significant risk factors.⁸² With regard to spine surgery, there are two broad populations to consider: patients with spine trauma or SCI and those undergoing nontrauma surgery.

Patients with spine trauma have a high risk of VTE with a baseline risk of 2.2% increasing to 5–6% in those patients with SCI.⁸³ The American College of Chest Physicians (ACCP) guidelines recommend patients with spinal trauma or SCI receive pharmacologic prophylaxis with either low-dose unfractionated heparin (grade 2 C) or low molecular weight heparin (LMWH) (grade 2 C). They further recommend that mechanical prophylaxis with intermittent pneumatic compression devices be added provided no contraindication to these devices exists (grade 2 C).⁸³ Finally, an inferior vena cava filter should not be used as primary prophylaxis.

The recommendations for VTE prophylaxis are less clear in patients undergoing nontrauma spine surgery where the benefit of pharmacologic prophylaxis must be weighed against the risk of postoperative hemorrhage. In this population, the baseline risk for VTE is very low. A retrospective review of 1,919 patients who all received LMWH demonstrated a risk of VTE of 0.05%. In this cohort, major postoperative hemorrhage attributable to LMWH occurred in 8 of 1,949 patients (0.4%).⁸⁴ Further surgical and patient factors may increase VTE risk including combined anterior-posterior approach, multiple operative levels, older age, prior VTE, and malignancy.⁸³ The ACCP guidelines recommend intermittent pneumatic compression devices be used for all patients undergoing spinal surgery (grade 2 C). For patients with high risk of VTE (as listed above), pharmacologic prophylaxis should be added to mechanical prophylaxis once hemostasis is achieved and the risk of postoperative hemorrhage decreases (grade 2 C).⁸³ Similar recommendations are advocated by the North American Spine Society.⁸⁵ There is no good evidence for the timing of these interventions. Intermittent pneumatic compression devices can be instituted at the beginning of the operation. North American Spine Society, based on weak evidence, recommended that when indicated LMWH could be started safely on the elective day of surgery. Because of the preventable morbidity and costs association with VTE, the Agency for Healthcare Research and Quality suggests that a VTE protocol be designed and implemented within an institution to improve rates of VTE prophylaxis.⁸¹

Pain Management in Spine Surgery

Pain management of patients presenting for spine surgery is a challenge for the anesthesiologist and surgeon for many reasons. Patients often have severe back pain or

radiculopathy preoperatively, and the severity of preoperative pain predicts postoperative pain severity, both of which predict higher probability of chronic postsurgical pain. Patients may be disabled and deconditioned by preexisting pain and they are often opioid tolerant.

Patients coming to surgery with high levels of preoperative pain can have a highly sensitized central nervous system (CNS). This makes management of their perioperative pain a challenge because pain can be amplified (hyperalgesia), nonpainful stimuli such as simple movements or light touch can become painful (allodynia) and pain can spread to noninjured tissue. Conventional simple analgesics and opioids may be less effective in the presence of a sensitized CNS, requiring higher doses and more analgesic agents for effective pain management. Preoperative opioid tolerance in itself can sensitize the CNS and cause amplified pain signals postoperatively, leading to increased postoperative consumption of analgesics and a positive feedback loop.

The nociceptive input of major spine surgery is more complex than many other surgeries. Large incisions crossing numerous dermatomes result in activation of peripheral nociceptors and cause extensive inflammation. Pain of musculoskeletal origin results from surgical manipulation of bones, muscles, ligaments, disks, and facet joints. Of all the deep somatic structures, the periosteum has the lowest threshold for pain transmission. Richly innervated periarticular tissues give rise to constant deep somatic pain, which results in severe reflex spasms of muscles supplied by the same or adjacent spinal cord segments.

Pain due to damage or compression of nerve tissue results in intense acute pain postoperatively. Poorly managed analgesia causes patient discomfort, a reluctance to mobilize, and delays discharge. Other complications are related to an exaggerated stress response and can include cardiovascular stress and complications, hyperglycemia, and delayed wound healing and infection. If left untreated, inflammation of nervous tissue initiates a cascade of biological events, sensitizing nerves peripherally and resulting in persistent CNS changes. The incidence of developing chronic pain after major surgery is estimated to be between 20% and 50%, and there is a correlation between the duration of acute postoperative pain and the incidence of persistent postsurgical pain.⁸⁶ The overall severity of pain over the first 7 days is a better predictor of developing a persistent pain state than the maximum pain score reported.^{86–88} Given the strong association between

preoperative pain, postoperative pain, and chronic postsurgical pain, good perioperative analgesia throughout the healing period beyond discharge from acute care is crucial.

Advances in understanding of the pain transmission pathway have lead to a multimodal approach to analgesia in spine surgery. Multimodal or mechanistic analgesia incorporates both opiate and nonopiate analgesics in the treatment of pain. Analgesics with differing mechanisms of action act synergistically to enhance analgesic efficacy, limit the dose of any particular medication, and thereby reduce dose-related adverse effects of these drugs while enhancing patient safety and satisfaction.^{88,89}

Analgesia management begins in the preoperative period with a thorough assessment and establishment of an analgesic plan tailored to the patient's pre-existing pain condition and the magnitude of the surgery. A subjective assessment of the intensity, quality, and timing of the patient's pain along with a functional assessment, including effects on sleep, activity, and mood, is important. The type, timing, and dosage of analgesic medications should be elicited. Patients taking opiates for a period of >4 weeks are prone to developing both tolerance and opioid-induced hyperalgesia, although there is significant patient-to-patient variability.⁹⁰ A history of adverse effects and intolerance to specific medications should be documented. Analgesics should be continued up until and including the day of surgery including sustained release and transdermal opiate formulations in order to prevent withdrawal.

Nonopioid analgesics are important contributors to the analgesic management. Acetaminophen is a synthetic, central acting analgesic that is recommended for the treatment of mild to moderate acute or chronic pain, which has been shown to decrease postoperative opioid requirements and lower pain scores in patients undergoing major orthopedic surgery.⁹¹ The main concern with acetaminophen is hepatic toxicity, which can occur with even minor overdoses.

Nonsteroidal anti-inflammatory agents (NSAIDs) block the peripheral transduction of noxious stimuli at the site of injury by inhibiting the arachidonic acid-cyclooxygenase (COX) pathways. There are two distinct isoforms of COX: COX-1 and COX-2. Cyclooxygenase-1 also has a role in platelet aggregation, gastric protection, and renal blood flow. Cyclooxygenase-2 expression is minimal at baseline and is upregulated with tissue injury.^{92,93}

Both nonspecific NSAIDs and selective COX-2 inhibitors have been studied in spine surgery. A recent meta-

analysis found the addition of NSAIDs to opioid analgesia to be superior to opioid treatment alone for patients undergoing nonfusion lumbar spine surgery.⁹⁴ Paracetamol, a COX-2 inhibitor, was found to be an effective adjunct to patient-controlled morphine in lumbar spine surgery. Patients who received paracetamol had lower pain scores and less morphine consumption.⁹⁵

The routine use of NSAIDs in spine surgery is controversial due to potential impairment of bone healing in patients receiving these drugs.^{96,97} The mechanism by which NSAIDs adversely affect bone ossification is not entirely clear. Prostaglandins play a pivotal role in the bone healing process, and NSAIDs exert their effects through inhibition of prostaglandin synthesis and reduction of the inflammatory response.⁹⁸⁻¹⁰⁰ A recent meta-analysis of retrospective studies looking at failed spinal fusion in patients exposed to NSAID therapy perioperatively revealed normal doses of both NSAIDs and COX-2 inhibitors in the short-term (<14 days) was not associated with failed spinal fusion. Exposure to higher, nonconventional doses of ketorolac was associated with an increased chance of nonunion. The effect of NSAIDs on bone healing may be dose dependent, and further study is needed to examine the safety of longer term exposure to NSAIDs and spinal fusion outcome.¹⁰¹

Gabapentin and pregabalin are neuromodulating medications that show promise in multimodal analgesic management of spine surgery. These medications act via the alpha-2 delta subunit of voltage-dependent calcium channels in the dorsal horn of the spinal cord and brain resulting in a decreased release of excitatory neurotransmitters, which would otherwise amplify the nociceptive pathway.¹⁰² Preoperative gabapentin improves analgesia and decreases opioid consumption in the immediate postoperative period.^{103,104} Pregabalin 150 mg pre- and postoperatively reduced opioid consumption in patients undergoing spinal fusion.¹⁰⁵ In another study, patients receiving pregabalin prior to spinal decompression surgery had improved quality of life up to 3 months following surgery.¹⁰⁶ Somnolence is a common side effect of both medications that needs to be considered and can limit their use perioperatively.

Ketamine is a nonselective *N*-methyl-D-aspartate receptor antagonist. *N*-methyl-D-aspartate receptor activation causes constant neural firing resulting in a "wind-up" phenomenon contributing to central sensitization in which altered neural pathways potentially lead to a persistent

pain state. Ketamine potentiates opioid-mediated analgesia and provides a significant opioid sparing effect.^{107,108} In a study of 26 opioid-tolerant patients undergoing spinal fusion surgery, patients receiving ketamine had significantly lower pain scores for the first 24 hours postoperatively, improved analgesia with physiotherapy, and consumed significantly less patient-controlled analgesia (PCA) hydromorphone compared with placebo.¹⁰⁹ The utility of ketamine in opioid-dependent patients undergoing major lumbar spine surgery was supported in a subsequent study.¹¹⁰ An intraoperative load and postoperative infusion of ketamine should be considered in opioid-tolerant patients coming for major spine surgery and may improve analgesia in these challenging patients.

Opioid medications remain the foundation of analgesia in spine surgery. In the preoperative period, the patient's usual opioids are continued up to the day of the surgery. Intraoperatively, intravenous opioids are administered to provide good initial postoperative pain control. For larger procedures involving multisegmental fusions, techniques such as intravenous opioid PCA combined with other medications, or neuraxial opioid and local anesthetic are used. In most cases, patients will be transitioned to oral opioids within 2–5 days postoperatively. Side effects of opioids are not insignificant and include constipation, nausea and vomiting, urinary retention, itching, and respiratory depression. Combining opioids with nonopioid analgesics will result in a lower overall opioid dose and can minimize these adverse effects.

The use of neuraxial analgesia in spine surgery has been extensively investigated and both spinal and epidural analgesia techniques with local anesthetics and opioids have been used. Studies using a combination of local anesthesia and opioids infused continuously through a surgically placed epidural catheter for spinal fusion surgery have shown inconsistent results.¹¹¹ The use of intrathecal opioid analgesia for spine surgery has been found to be an effective modality in the immediate postoperative period; however, there is no support for long-term benefit and there tends to be an increase in unwanted adverse events such as respiratory depression and pruritis.¹¹¹ Overall, studies have not supported the routine use of neuraxial analgesia outside of scoliosis correction. In studies examining the use of epidural analgesia for both posterior and anterior approaches to scoliosis correction, patients who received a surgically placed epidural experienced better postoperative analgesia, earlier return of bowel function, fewer side effects, and higher patient satisfac-

tion.^{112,113} A meta-analysis examining the use of epidural analgesia for adolescent patients undergoing scoliosis correction demonstrated lower pain scores in the epidural group at 24, 48, and 72 hours following surgery.¹¹⁴

Complications during Spine Surgery

Air Embolism

Entrainment of air via open venous channels leading to air embolism is classically associated with the sitting position for surgery where the vertical distance between open venous channels at the operative site and the central circulation is increased. Depending on the venous pressure, a positive pressure gradient exists between the atmosphere and the central venous compartment. There are several reports of venous air embolism (VAE) verified at autopsy in surgery in the prone position,¹¹⁵ and it has been postulated that VAE is underreported in spine surgery.¹¹⁶

Risk factors for VAE in spine surgery include major blood loss and hypovolemia, hip and knee flexion,^{117,118} and spontaneous ventilation. Patients with an atrial septal defect are at risk for systemic air embolism through right to left shunting. Autopsy evidence of intracoronary and intracerebral air has also been demonstrated to occur even in the absence of anatomic shunts.¹¹⁵

Monitoring for VAE and its treatment can take many forms. Clinical features of VAE include a precipitous drop in end-tidal carbon dioxide, often accompanied by hypotension and other indicators of diminished cardiac output. Air entrainment can be identified using precordial Doppler, stethoscope, or ultrasound. Treatment of VAE consists of simultaneously stopping further entrainment of air, facilitating clearance of air already entrained, and supporting the circulation. Flooding the field with saline and obstructing venous channels stop further entrainment of air. Intravascular volume expansion and vasopressor administration increases central venous pressure (CVP), reduces further entrainment, and provides circulatory support. Although left lateral and head down position can theoretically attenuate flow of air via the pulmonary outflow tract, this position can be impractical in the prone patient. Early chest compressions are advocated to promote movement of air from the pulmonary artery into smaller vessels where it can be more rapidly eliminated by the lung. Ventilation with 100% oxygen increases the gradient between intravascular air (nitrogen) and alveolar gas to enhance elimination and provides maximally oxygenated blood during a time of reduced perfusion. A central venous catheter or multiorifice atrial catheter may also be aspirated to remove air.¹¹⁸

Postoperative Vision Loss

Postoperative visual loss (POVL) is a rare but devastating complication with multiple etiologies. Its prevalence in spine surgery has been estimated in the range of 0.02%.¹¹⁹ Anterior ischemic optic neuropathy, posterior ischemic optic neuropathy (PION), central retinal artery occlusion, and cortical blindness are all possible causes. An analysis of POVL cases in spine surgery patients revealed PION to be the most common diagnosis.¹²⁰ A recent case-control study identified six independent risk factors for PION after spinal fusion surgery: male gender, obesity, use of the Wilson frame, duration of anesthetic, blood loss, and lower percent colloid administration.¹²¹ Recommendations for perioperative management from this study, as well as a practice advisory from the American Society of Anesthesiologists, include considering specific mention of POVL during patient consent for surgery, continuous monitoring of blood pressure and possibly CVP, use of colloids along with crystalloids, keeping the head at or above heart level and neutrally positioned, and consider staging long surgeries.¹²² No specific recommendations regarding deliberate hypotension or specific transfusion threshold are supported by the currently available evidence.

Monitoring for Neurologic Injury

Intraoperative neurophysiologic monitoring techniques are utilized in spine procedures where neurologic injury can occur. An anesthetic technique to facilitate accurate, reliable, and reproducible conditions for intraoperative monitoring requires understanding of the monitoring techniques, knowledge of the effects of anesthetics on intraoperative monitoring, and communication between anesthesiologists, surgeons, and neurophysiologists. Regardless of the intraoperative monitoring techniques or the anesthetic regimen employed, once baseline neurophysiologic signals have been recorded, significant changes in anesthetic depth during key portions of surgical intervention are avoided to reduce confounding influences on signal integrity at a time when the monitoring modality is most useful.

Commonly used intraoperative monitoring techniques during spinal surgery are somatosensory-evoked potentials (SSEPs), motor-evoked potentials (MEPs), and the intraoperative wake-up test. Somatosensory-evoked potential monitoring is used during spinal surgery to assess for injury at the nerve root or dorsal column level. While not degraded to the same extent as MEPs, SSEPs exhibit a dose-related increase in latency and decrease in amplitude

under volatile anesthesia and volatile agents should be dosed below one MAC (minimum alveolar concentration) to maintain SSEP signal quality. Opiates are often coadministered with volatile agents and do not affect signal quality. Nitrous oxide is typically avoided as it results in further degradation of the signal. The use of intravenous anesthetics such as propofol, thiopental, or midazolam infusion results in superior signal quality compared with volatile agents. Ketamine and etomidate are reported to increase the amplitude of SSEPs, though the effect that this has on their sensitivity and utility remains a matter of speculation. Neuromuscular blocking agents have no effect on SSEPs.¹²³

Of the monitoring techniques described for spinal surgery, MEPs are most sensitive to anesthetics. Preliminary work showed that MEPs were extremely sensitive to anesthetics even at subclinical doses.¹²⁴ Subsequently, use of multipulse stimulation techniques improved both low amplitude baseline signals and anesthetic depressed MEP signals. All anesthetics cause a time-dependent decrease in MEP signal amplitude, proportionate to the length of surgery regardless of the anesthetic regimen referred to as “anesthetic fade.”¹²⁵ Anesthetic fade can be overcome by increasing stimulation energy but this may lead to false-positive signal changes.

All currently used agents cause significant dose-dependent depression of MEP signals. Although MEPs are recordable with desflurane or sevoflurane at 0.5 MAC, there is little evidence to show adequate clinical recording conditions with a volatile anesthetic as compared with total intravenous anesthetic options.^{126,127} Propofol is currently the most popular anesthetic agent for the maintenance of anesthesia during MEP monitoring due to its titrate ability and favorable pharmacokinetic profile. Propofol at clinically relevant concentrations does not significantly affect MEP responses.¹²⁸ Although bolus administration of propofol can lead to loss of MEP signals, signals return within minutes.¹²⁹ Other intravenous anesthetics, including midazolam, ketamine, and etomidate, do not clinically significantly suppress MEPs. At target-controlled plasma concentrations, remifentanyl has the least effect on MEPs, although all opioids produce adequate recording conditions.¹³⁰

Neuromuscular blockade is frequently used to facilitate tracheal intubation and surgical exposure. Boluses of muscle relaxants lead to loss of MEPs, as they block signal transduction at the level of the neuromuscular junction. Careful infusions of neuromuscular blockers with 20–50% maintenance of single twitch height have been shown to

allow reliable MEP recordings when used in conjunction with a minimally suppressant anesthetic and multipulse transcranial electrical MEP.¹³¹ Patients with preoperative neurologic deficits appear to be more sensitive to the depressant effects of neuromuscular blocking drugs.¹³² A short acting neuromuscular blocking agent may be used at the time of induction of anesthesia; however, maintenance of neuromuscular blockade or rebolusing can pose considerable challenges to MEPs interpretation.

Intraoperative Wake-up Test

The wake-up test involves emerging a patient from a general anesthetic during a surgical procedure to allow clinical assessment of the patient's neurologic function (following commands to move hands and feet). The wake-up test is simple to perform and requires no neurophysiologic equipment or staff. It can be used in conjunction with neurophysiologic monitoring such as MEPs to allow for clinical correlation when electrophysiologic changes are detected. For a wake-up test to be clinically practical, a general anesthetic technique that allows for rapid emergence is desirable. Maintenance of anesthesia with either desflurane or propofol along with a remifentanyl infusion can facilitate performing a clinical neurologic examination in as little as 5 minutes.¹³³ Use of remifentanyl in spinal surgery has its limitations as remifentanyl does not provide any postoperative analgesia and may lead to postoperative hyperalgesia. If remifentanyl is chosen as an intraoperative opioid to facilitate a rapid wake-up test, the patient will require other analgesics prior to the completion of surgery for adequate initial postoperative analgesia. Sufentanil or fentanyl may be more clinically appropriate opioids for infusion during spinal surgery, although time to perform a wake-up test will be delayed.

KEY POINTS

- Perioperative optimization of patient comorbidities affects patient and surgical outcomes and requires a multidisciplinary approach to reduce perioperative complications.
- Patients with acute cervical spine injuries are at risk for ventilatory failure requiring intubation. Intubation needs to be undertaken with care to avoid secondary SCI. Patients with SCI should have an MAP maintained at 85–90 mm Hg for the first 7 days following acute SCI.

- Preoperative anemia is common and associated with postoperative mortality. A multidisciplinary blood management program can optimize patients prior to surgery and reduce the requirement for allogeneic transfusion of blood products.
- In these challenging patients, it is imperative to treat perioperative pain resulting from spine surgery aggressively using a multimodal approach to prevent long-term sensitization of the CNS and the development of a chronic pain state.
- Prone positioning during spine surgery is associated with complications including VAE and postoperative vision loss. These complications should be anticipated and steps taken to reduce associated modifiable risk factors.

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In this observational study, preoperative anemia was common in noncardiac surgery patients and associated with increased mortality. The authors suggest treatment of preoperative anemia to reduce perioperative risk.

Sharma S, Balireddy RK, Vorenkamp KE, et al. Beyond opioid patient-controlled analgesia: a systematic review of

analgesia after major spine surgery. *Reg Anesth Pain Med*. 2012;37:7998.

Non-opioid analgesic modalities available for the treatment of pain for both minimally invasive and invasive spine surgery are discussed in this extensive review.

Lee LA, Roth S, Posner KL, et al. The American Society of Anesthesiologists Postoperative Visual Loss Registry: analysis of 93 spine surgery cases with postoperative visual loss. *Anesthesiology*. 2006;105:652-9.

Male gender, obesity, use of the Wilson frame, duration of anesthetic, blood loss, and lower percent colloid administration have been identified as independent risk factors for postoperative visual loss after spinal fusion surgery. It is recommended to consider specific mention of POVL during patient consent for surgery, continuous monitoring of blood pressure and possibly CVP, use of colloids along with crystalloids, keeping the head at or above heart level and neutrally positioned, and consider staging long surgeries.

Spinal Orthoses

Christopher Bailey, Parham Rasoulinejad, Abdulaziz Alkuwari, David Hannallah

Snapshot

- » Cervical Orthosis
- » Selection of the Appropriate Orthotic
- » Thoracolumbosacral Orthosis
- » Thoracolumbar Trauma
- » Degenerative Conditions

INTRODUCTION

The spine can be divided into five segments based on anatomic and biomechanical considerations, including C1-2, C3-T1, T2-T10, T11-L4, and L5-sacrum. Each of these segments is unique and should be considered differently with respect to orthosis use. However, for organizational purposes, this chapter will be subdivided into cervical and thoracolumbosacral segments.

US Food and Drug Administration (FDA) clearance is not required prior to clinical use of spinal orthoses as the FDA categorizes all spinal orthoses as class I devices. Therefore, spinal orthoses can be manufactured and marketed for public use without rigorous proof of safety or efficacy.¹ Currently, spinal orthosis is prescribed for many different reasons including deformity correction, fracture stabilization, or simply to limit physiological spinal motion associated with degenerative conditions or to provide the patient with proprioceptive feedback.

The principle of preventing motion in the adjacent joints, as used in the extremity, also applies to the spine. However, due to the multisegmental nature of the spine, the junctional levels adjacent to the injured segment must be immobilized. As such, when stabilizing the cervical spine, the head and the thoracic spine must be immobilized and when stabilizing the lumbar spine, the pelvis and the thoracic spine are immobilized. Compared to surgical management of spinal disorders, the use of orthosis may seem benign; however, it is not without risks and

complications. These devices have been associated with skin irritation, muscular atrophy, osteopenia, joint stiffness, mortality, and severe discomfort.²⁻⁸ Orthoses can be particularly troublesome in the obese patients.

CERVICAL ORTHOSIS

The unique anatomy within the upper cervical spine and subaxial spine makes immobilization challenging, and different devices are required depending on the location of the injury. The stabilization of the cervical spine depends on immobilization of the skull, usually via occiput and the mandible proximally and the clavicle and/or thorax distally.¹ Hard contact against the mandible and occiput is associated with skin complication and impairment of mandibular movement can interfere with mastication. Increased rigidity of the device can increase these associated risks. Distal immobilization is challenging because the clavicle moves with shoulder motion and the soft tissues around the shoulder and the upper trunk are variable in size and shape. All of these factors along with the degree of injury must be taken into consideration. The clinician must choose a device that meets the patient-specific needs while minimizing complications.

The primary indication for the use of cervical orthosis is instability. This includes instability caused by trauma, tumor, infection, inflammatory diseases, and iatrogenic instability postsurgery. Orthosis is also used for the treatment of chronic or degenerative disease of the cervical spine, including radiculopathy or myelopathy.

Cervical orthoses are divided into four general categories: the cervical collar, the poster brace, the cervicothoracic orthosis (CTO) brace, and the halo ring-vest fixator (Figs. 14.1 to 14.6). The cervical collar comes in soft and hard varieties and generally extends from the occiput and mandible down to the clavicle. The poster brace and the CTO are similar devices with the CTO extending slightly more distal and incorporating more of the chest usually with a circumferential strap, while the poster brace is best described as a cervical collar with extension down to the chest and/or the back. Cervicothoracic orthoses and poster braces control the head through padded mandibular platforms and supports at the back of the occiput. Rigid up-rights then attach the head to the thorax via thoracic plates and/or straps. The halo fixator is a device that connects the head to the thorax via pins that pierce the outer table of the calvarium and subsequently attach to a vest around the chest via rigid metal ring and bars. More extensive versions of the halo fixator connect the head to the body via plaster of paris body cast or pins in the pelvis.

Cervical Collar

Among of all the options, the soft collar (Fig. 14.1) is the least stabilizing prosthesis,^{9,10} providing no more stability than a

turtle neck sweater.¹¹ However, it is also the least expensive and is associated with little patient discomfort. This device is only indicated to provide proprioceptive feedback to the patient. Neck pain post-trauma may be treated with a soft collar for a short period as long as no potential for instability exists.

The most commonly used cervical orthoses are rigid cervical collars; examples are demonstrated in Figures 14.2 and 14.3. There are also custom-made variations of each, but they will collectively be referred to as cervical collars. These collars tend to be effective in minimizing motion in the sagittal plane and to a lesser degree for lateral bend and axial rotation.¹² Multiple biomechanical studies have compared the effectiveness of these devices. Most commercially available cervical collars appear to be effective in immobilizing the spine, although the custom-made varieties are more comfortable.^{1,8,10-14} These devices are commonly used prophylactically in trauma patients until the cervical spine is safely cleared. It is important that these devices be removed as soon as injury to the cervical spine is ruled out. Beyond the complications of skin irritation, difficulty with ingestion and speaking as well as general discomfort, rigid collars may cause increased intracranial pressure, which can be perilous in patients with traumatic brain injury.²

Cervicothoracic Orthosis

The CTOs such as the Minerva (Fig. 14.4) or SOMI (sternal-occipital-mandibular immobilizer) brace (Fig. 14.5), as well as other custom orthoses, are designed to stabilize the cervical spine by immobilizing the occiput and the chest. Cervicothoracic orthoses have been shown to be more effective than cervical collar and are a good option for immobilization of the cervical spine.^{12,13,15} The Minerva is an effective brace and in some instances has been shown to be more effective than halo immobilization as it does not lead to the snaking phenomenon.¹⁶ Nonetheless, with the introduction of the halo, the use of CTOs has decreased.¹

Halo-vest Device

The halo-vest device is generally accepted as the most effective method of upper cervical spine stabilization, even though the halo allows for substantial motion in the lower cervical spine.¹⁰ Furthermore, the halo can be associated with a snaking phenomenon, whereby neck muscle contraction causes translation of individual vertebrae in the midcervical spine due to immobilization of the



Fig. 14.1: Soft collar.



Fig. 14.2: Hard collar (Miami J).



Fig. 14.3: Hard collar (Philadelphia collar).



Fig. 14.4: Cervicothoracic brace (Minerva).

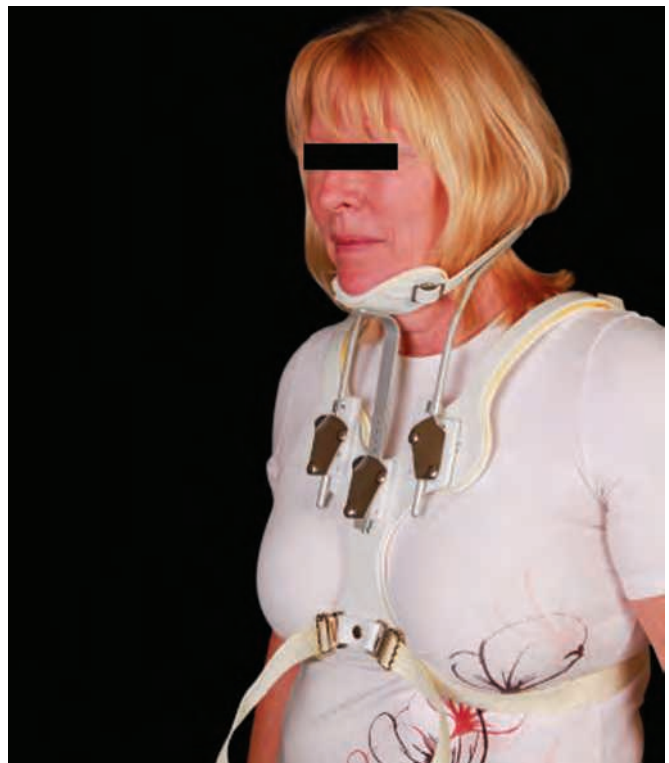


Fig. 14.5: Cervicothoracic brace (sternal-occipital-mandibular immobilizer).



Fig. 14.6: Poster brace.

upper and lower segments.¹⁰ The halo device is commonly used to stabilize the cervical spine when the rigid collar and CTOs are deemed to be insufficient. A more recent biomechanical study comparing a rigid collar, a soft collar, and CTO to a halo, found the halo to be the most effective device in stabilizing the spine.¹⁷ However, other studies have found the halo to be less effective than a rigid cervical collar in stabilizing the middle or lower segments of the cervical spine.¹⁰ When using this device, careful consideration must be given to patient selection to avoid complications. Absolute contraindications to the use of the halo include cranial fractures, infections, and severe soft-tissue injury at proposed pin sites. Relative contraindications include chest trauma, obesity, pregnancy, advanced age, and Barrel-shaped chest.³ The elderly population is particularly at high risk of halo-related complications. Many authors have reported a high rate of complications associated with halo use in elderly (>65 years).⁶ The mortality rate of elderly patients treated with halo has been reported to be as high as 40%, with one group reporting a two-fold increase in mortality and major complication rate in elderly patients treated with halo compared to those treated with cervical collar.^{6,7,18} Horn et al. have also reported high

complication rate with halo use in the elderly; however, they concluded that the high complication rate was due to multiple comorbidities seen in this population.⁵ Others have also compared halo fixation to posterior cervical fusion for odontoid fractures in the elderly and concluded that the risk of surgery, although not trivial, is less than the reported risks of halo treatment.¹⁹ Although the majority of these studies are based on small patient populations with limitation in randomization and blinding, the use of a halo in the elderly is a relative contraindication. Also, complication of screw loosening, loose fixation, pin site infection, skin necrosis, and even intracranial penetration from a fall can occur.^{4,20} Another option to the halo is the Lerman noninvasive halo system, which has been shown to be very effective in children.²¹ This noninvasive halo system can provide children with congenital torticollis, C1-C2 rotatory subluxation, and odontoid fractures with immobilization without the risk of pin penetration into the skull.²¹

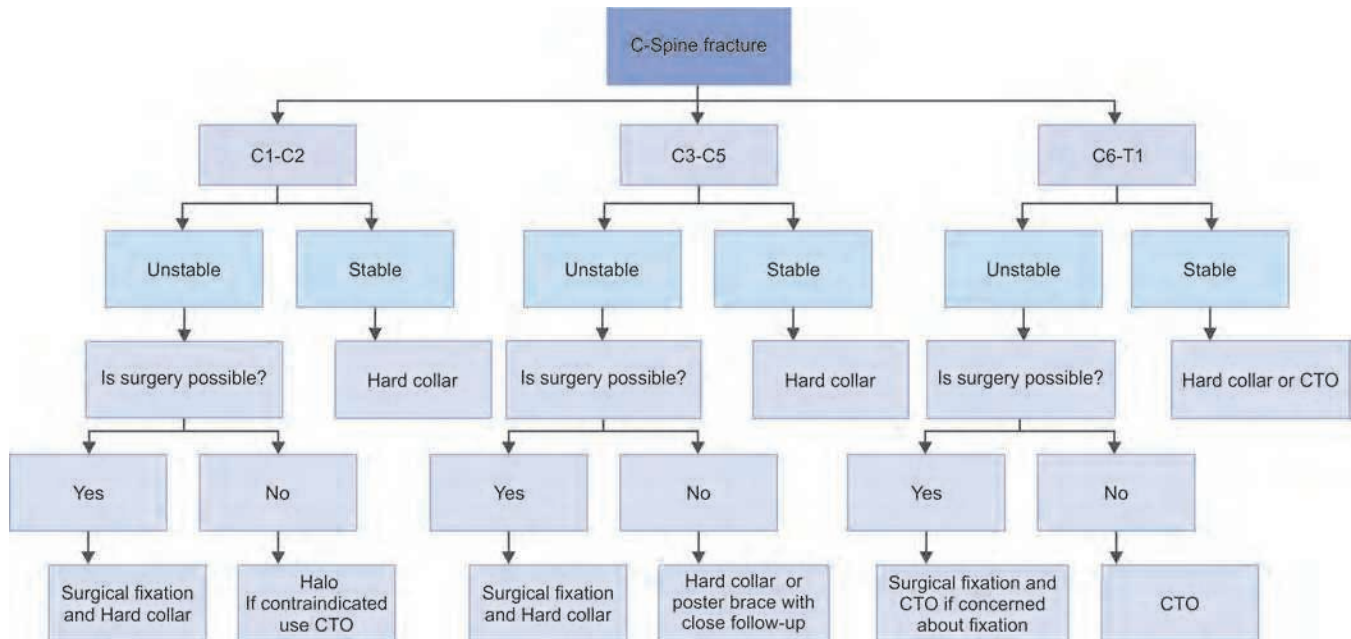
Poster Brace

Multiple varieties of the poster brace have been manufactured in an attempt to better control motion at the cervicothoracic junction. Most of these are modifications to hard cervical collars that extend down to the thorax. Effectively, poster braces junction much like the SOMI or Minerva.

SELECTION OF THE APPROPRIATE ORTHOTIC

In this section, recommendations are made toward the selection of cervical orthotic use in the treatment of common spinal trauma. These recommendations are summarized in Flowchart 14.1. In each scenario, careful follow-up with standing or sitting X-rays in the orthosis is essential. For all fractures, the indications for surgical intervention must be excluded prior to initiating conservative care. Indications for surgical intervention are discussed in detail within other chapters of this textbook.

For fractures of the atlas (C1), determination of fracture stability must be made, which is based on the integrity of the transverse ligament. If the transverse ligament is disrupted, the fracture is considered unstable as significant instability is likely to exist between the first and the second vertebra. Significant displacement of the C1 lateral masses will lead to malalignment of the C0-C1 and/or C1-C2 articulations. For unstable fractures of atlas, surgical management in the form of reduction and instrumentation

Flowchart 14.1: Algorithm for management of cervical spine fracture.

followed by hard collar immobilization for up to 3 months is recommended. However, an alternative to surgical fixation is the use of the halo-vest device. If the halo-vest device is otherwise contraindicated, then a CTO should be considered. If the fracture is stable, treatment with a hard collar for approximately 3 months with routine clinical and radiographic follow-up to confirm fracture union should be undertaken.

There are multiple patterns of axis (C2) fractures; however, the two most common are the odontoid fracture and hangman's fracture. Spinal stability must once again be determined. Generally, displaced fractures at the base of the dens (type II) and hangman's fractures with disruption of the C2-C3 disc space are unstable. As such, surgical fixation should be considered for these fractures.²² Alternative treatment to surgical management is halo-vest stabilization with or without closed reduction. In the elderly, in whom halo-vest stabilization may be contraindicated, we recommend a CTO; however, in some circumstances, patient factors may indicate a simple hard collar for the treatment of type II odontoid fractures. In the case of stable hangman's fractures or dens fractures (example most type I and type III), we recommend the use of a hard collar or CTO with routine follow-up until fracture union.

Injuries of the middle cervical spine including fractures from C3 to C5 are the most difficult to immobilize

with an orthosis as biomechanical studies have shown that the mid-cervical spine is the most difficult part of the cervical spine to control with a brace. If the fracture pattern is stable with no substantial malalignment or cord compromise, use of well fitted hard collar for approximately 3 months is recommended. However, if the fracture pattern is unstable, then surgical management must be considered. Further consideration for the use of a hard collar postoperatively can be made if any doubts exist as to patient reliability, to protect the soft tissues, or immobilize associated injuries. Fractures of the cervical spine below the C5 level should be immobilized with a CTO. For simple injuries such as isolated spinous process fracture or transverse process fracture, a soft collar prosthesis is likely all that is needed. In some cases, a cervical collar can actually increase cervical motion during certain activities such as eating.

■ THORACOLUMBOSACRAL ORTHOSIS

Bracing for Treatment of Deformity

The spinal deformity for which orthoses are most commonly used is scoliosis in attempt to halt progression; however, studies have failed to show that bracing will reverse any existing deformity and the use of bracing to treat scoliosis is viewed as futile by some. Classic indication

for orthotic use in adolescent idiopathic scoliosis is the treatment of skeletally immature patients with curves that measure 30–45°, or the radiological progression of the curve >5° in patient in whom a previously recorded measurement was 25.²³ Treatment of idiopathic scoliosis with orthosis is generally continued until full skeletal maturity unless further progression despite brace use necessitates surgical management. In other forms of scoliosis such as neuromuscular or congenital scoliosis, bracing is ineffective in inhibiting progression; however, it can be used as a temporary measure until surgery is performed or as an alternative treatment when surgery is not possible. Other types of spinal deformity can also be treated with bracing; in particular, Scheuermann's kyphosis can be treated with satisfactory outcome in patients with curves of 50–55.²⁴

Biomechanics of Bracing Spinal Deformity

Braces are used to correct sagittal and coronal deformity by applying corrective external pressure forces at osseous structures that are attached to the vertebral column. The ribs and the sternum are used to apply corrective forces on the dorsal spine; the pelvis is used as a contact point for lumbar spine. Correction of the coronal deformity is done by applying three-point bending forces to the thoracic curve, pressure applied to ribs corresponding to the apex of the deformity, whereas the pelvis and the axilla serve as the opposing contralateral pressure points. For lumbar curve deformities, pressure is applied to the level of the deformity with contralateral pressure applied to pelvis and the thorax. Correction of sagittal deformity is done by applying pressure over the sternum and anterior superior iliac spine anteriorly and the spinous processes posteriorly. The amount of pressure applied can be adjusted by varying the thickness of the pads over the pressure areas. An increase in pad thickness over pressure areas will increase the amount of correction yielded. The magnitude of correction is also controlled by the height of axillary pads, with higher pads leading to greater correction by increasing the moment arm.^{25,26}

Complications of Bracing

The use of brace for the treatment of scoliosis is not completely benign. Most patients find the brace to be very uncomfortable and a significant social inconvenience.

Skin irritation and pigmentation can also occur, especially in hot climate regions. Furthermore, brace use has been associated with significant respiratory impairment in patients with neuromuscular scoliosis.²⁷ Another major issue with brace wear is compliance. As such, proper patient and parents counseling is essential and psychological assessment has been advised as means of improving compliance.²⁸ Many authors have investigated patient compliance with brace treatment: Helfenstein et al.²⁹ used a temperature probe to record the temperature at the skin-brace interface, while Rahman et al.³⁵ used similar methods of measurements and were able to demonstrate a correlation between time spent in brace and success of treatment.²⁹

Types of Orthosis Available for Scoliosis

Milwaukee Brace

The Milwaukee brace is a custom-made cervicothoracolumbar orthosis used in the treatment of scoliosis. The device is a full torso brace, which extends from the skull to sacrum. The Milwaukee brace can be used for curves that extend above T8. This brace utilizes rigid metal bars to connect a thoracolumbar rigid brace to a cervical component; as such, it is generally poorly tolerated and is rarely used at our center.

Charleston Brace and Boston Brace (Figs. 14.7A to D)

The Charleston and the Boston brace are custom-made thoracolumbosacral orthoses, which work by applying three-point bending forces to the thorax and pelvis. These braces are most commonly prescribed at our center and at most other centers in North America. They are effective forms of bracing for curves with apex below T7 and above L2. The Boston brace has been shown as an effective treatment modality for idiopathic scoliosis, perhaps decreasing the need for surgery and in some cases more effective than the Charleston.^{30,31} The Charleston brace is prescribed for nighttime use only and it is too uncomfortable and cumbersome to consider for use during the day. The brace holds the patient in overcorrected position. Despite reduced wear schedule, patient compliance was poor due to the discomfort frequently reported with its use. This can be an excellent option for patients who are not willing to wear the brace during the daytime. The more classic Boston brace is designed to be more cosmetic and comfortable and to be worn during the day as well as nighttime.



Figs. 14.7A to D: Charleston brace in pink and Boston brace in white.

Providence Brace

Providence brace is another brace for dedicated nighttime use. Curve correction occurs through application of lateral and derotational forces. It results in a tilt of the shoulder and truncal rotation, making walking or even standing in the brace very difficult.¹⁵

SpineCor Brace

SpineCor brace is an example of a nonrigid brace, which works on the principle that scoliosis is caused by postural disorganization, muscular dysfunction, and unsynchronized spinal growth. The SpineCor brace consists of thermo-plastic pelvic base, thigh and crotch bands, a cotton bolero,

and four corrective elastic bands of variable sizes. It is worn full time and it is relatively comfortable with a very low profile making it less visible under clothing. The effectiveness of this brace has been demonstrated by Coillard et al. who reported a 95% success rate in their carefully selected patient population.³²

Progressive Action Short Brace

The progressive action short brace (PASB) is a less bulky brace compared to the more traditional Boston type braces, allowing freedom of movement of trunk and wearing clothes beneath. For these reasons, compliance is reported to be higher with satisfactory results.³³ This brace works by a different mechanism than the three-point bending force theory. The biomechanical principle is to constrain spine dynamics and inhibit curve progression by inverting the abnormal load distribution during growth. The biomechanical concept is to apply external forces aimed at producing a partial reduction of the deformity that is followed by a generation of continuous internal corrective forces.

In summary, we advocate the use of spinal orthosis in the treatment of scoliosis. The clinician must take into account patient factors, deformity factors, as well as the experience and abilities of the local orthotist. Generally speaking, for curves above T8, the Milwaukee brace should be considered. For curves below this, the Boston brace, Charleston, Providence, Spinecor, as well as PASB are all potential options.



Fig. 14.8: Jewett brace.

cautioned to not become dependent on bracing as this can result in atrophy of the core muscles and long-term dependence on the brace. Patients should be cautioned to use a lumbar brace intermittently as part of the larger treatment protocol that includes core strengthening and physical therapy.

THORACOLUMBAR TRAUMA

Orthoses are commonly utilized for the nonoperative treatment of many fractures within the thoracolumbar spine. The wedge fracture, burst fracture, and seat-belt injury are appropriate fractures to be treated with a brace. For these fractures, the deforming force to be braced against is within the sagittal plane. The use of a hyperextension type orthosis, such as the Jewett brace (Fig. 14.8), has demonstrated very good outcomes.³⁴ When the fracture is also potentially unstable in the coronal plane, an off-the-shelf or custom-made thoracolumbosacral orthosis should be considered.

DEGENERATIVE CONDITIONS

Spinal orthoses can also be useful in treating painful degenerative lumbar conditions by providing support to the core muscles in the lumbar spine. While lumbar braces can effectively alleviate back pain, patients should be

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Measuring Outcomes in Spinal Surgery

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Snapshot

- » Time Points for Data Collection
- » Data Sources for Measuring Outcomes: Physicians, Processes, and Patients
- » Patient-Derived Outcome Instruments: General Health versus Disease Specific
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- » Utility Scores for Spinal and Nonspinal Pathology
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INTRODUCTION

Shifts in measuring success of treatment and in the doctor-patient relationship over the past 20 years have substantially impacted the manner in which patient outcomes are measured, particularly in surgical fields. Where outcomes were once largely reported in terms of technical success or failure of an operation, the evolving recognition that healthcare is consumer-driven has drastically increased the importance placed on patient satisfaction and recovery of function when measuring elective surgery outcomes.

A second paradigm shift that is less well established at the time of publication of this textbook, but certain to become increasingly important in coming years is the measurement of the success of treatment on a cost basis. The unsustainable pace of increasing healthcare costs in many western countries, particularly the United States, has drawn interest to the use of outcome metrics to measure the relative cost-benefit proposition of different treatments and some healthcare systems have begun to rely on these instruments and the associated analysis to make decisions about rationing healthcare. While such practice is not yet widespread, the mounting pressure on payors leaves little doubt that treatments will need to be justified

on a cost-effectiveness analysis (CEA) basis in the near future. This heavy fiscal influence on the practice of medicine creates an imperative for physicians to develop at least a working understanding of the concepts underlying CEA to ensure that outcome measurement accurately captures the benefit provided to patients by appropriately indicated and provided treatment.

TIME POINTS FOR DATA COLLECTION

The minimum publishable follow-up period for all spinal reconstruction surgery is typically 2 years. It is the author's practice to collect outcome instruments at baseline and then postoperatively at 3 months, 6 months, 1 year, and 2 years. Although some investigations may require even longer follow-up, we typically collect data after 2 years only when needed and do not routinely follow patients without new or persistent complaints in order to reduce the financial and personnel burden associated with data collection. Although some procedures such as microdiscectomy may be reasonably discharged after 1 year of symptom-free follow-up, it is our practice to follow all patients for 2 years and collect outcome instruments at intervals specified above.

DATA SOURCES FOR MEASURING OUTCOMES: PHYSICIANS, PROCESSES, AND PATIENTS

Physician-derived outcome measures were once widespread and have the advantage of being easily and inexpensively collected without the need for patient questionnaires and the associated cost and time. These few advantages are heavily outweighed by the physician bias toward favorable results, reliance on physician subjectivity to identify qualitative outcome categories (i.e. excellent vs. satisfactory), uncertainty as to whether these measures capture outcomes important to patients and the inability to compare outcomes across different diagnoses, a necessary feature for CEA. While western medicine has appropriately moved away from the use of physician-derived outcome measures, these measures are still useful in some databases compiling results when patient-derived outcome measures are not used or not of primary concern such as the American Board of Orthopaedic Surgeons' board collection database.

Process-based outcome measures are recorded at the time of delivery of care and usually quantify some aspect of treatment. Examples relevant to spinal surgery include operative time, intraoperative blood loss, length of hospital stay, whether the patient received preoperative antibiotics, and readmission rate after surgery. These measures are recorded as a part of medical record documentation and accessible from surgical, nursing, anesthesia, billing, or hospital records. Because they can be retrospectively queried and do not require any departure from the typical delivery of care, they are minimally burdensome to collect. Process-based measures are usually objective and may be less biased than some physician-based or patient-based measures and often can be interpreted or analyzed using simple methods. Process measures, however, often do not reflect patient's quality of life and function, qualities that are increasingly important in describing surgical outcomes. Furthermore, process measures can be gamed by physicians and hospitals without significant changes in the quality of care provided. Process-based measurements are used in some instances in the absence of patient-centered outcome measures to determine reimbursement rates such as has been implemented with the Surgical Care Improvement Project (SCIP) measures. To improve care in these areas, the program has identified nine specific process measures that are tracked nationally. While reporting by hospitals is voluntary, Medicare will decrease reimbursements by 2% if a hospital does not report its rates

of compliance. This type of reporting may be used in the future to more strongly influence reimbursement rates. While such use of process measures is likely misguided due to the uncertain impact on patient outcomes, it is likely to continue in the future if payors are not provided with better patient-centric data on which to base decisions and reimbursement, particularly given the ease of collection of process measure data.

The use of patient-derived outcome measures reflects a growing recognition that outcomes in healthcare should describe patient's function and quality of life. Strengths of patient-derived outcome measures include direct insight into how the primary consumer of healthcare perceives his/her outcome and the ability to learn about less tangible factors that are not captured during a brief encounter with a physician and would not be reflected by physician-driven measures but are nonetheless important to patients. There are many challenges in using patient-derived measures that practically limit their use, including the time-consuming nature of many of the questionnaires for patients and the additional infrastructure necessary to distribute, gather, score, and catalog the questionnaires. These tasks usually will fall on the physician and are not reimbursed. Some instruments are proprietary and associated with an additional cost for interpretation. Physicians must have a strong motivation to perform research or to carefully monitor their patient's outcomes to take on the extra workload and cost. Finally, most questionnaires cannot be completed by patients with cognitive limitations and functional components may not accurately represent the outcome for patients with severe physical limitations, patient populations who equally deserve to have outcomes measured and optimized.

PATIENT-DERIVED OUTCOME INSTRUMENTS: GENERAL HEALTH VERSUS DISEASE SPECIFIC

Outcome measures used in spinal surgery may be designed to provide general information about a patient's function and well-being or may be more focused on a specific region of the spine or even a certain spinal condition. Examples of general health instruments are questionnaires such as the Short Form-36 (SF-36) or EuroQol-5D (EQ5D). General health measures are attractive because they allow comparison between patients with different diseases and because some of these instruments can be used in cost-effectiveness calculations by surgeons, researchers, and interested governmental and payor organizations. Downsides include

the lack of specificity to the condition being treated and greater potential for confounding effects by concurrent treatment of nonspinal pathology, which may change scores independent of spinal treatment. Most research on treatment of spinal diseases will use both a general health and disease-specific outcome measure to overcome some of these limitations.

General Health Outcome Measures

The SF-36 is a proprietary instrument developed systematically as a part of the Medical Outcomes Study (MOS), which was first described in 1982.¹ The survey includes 36 questions that the patient answers by selecting from five provided responses, yielding a composite score in eight different health domains grouped into physical or mental domains. It does not, however, provide a single composite score and cannot be graded without entering into a fee-based licensing agreement (*QualityMetric*, Lincoln, RI). Two domains (bodily pain, physical functioning) have been used as independent outcome measures in the spine surgery literature, most prominently in the Spine Patient Outcomes Research Trial (SPORT) studies.²⁻⁴ The SF-36 has been translated into numerous languages and validated many times.⁵⁻¹⁰

Shorter versions of the SF-36 have been developed to reduce the length of time it takes to complete and score the questionnaire, resulting in the SF-12 and SF-6D. Both questionnaires consist of a subset of SF-36 questions demonstrated to most closely predict the SF-36 domain scores based on regression analysis. One limitation of both shorter questionnaires is that they cannot be broken into the same eight health domains that make up the SF-36, but are only broken down into physical and mental subscores. The SF-12 has been validated for use in patients with low back pain¹¹ and cervical myelopathy.¹⁰ Practically speaking, the SF-12 is widely used and there is no pressing need to demonstrate validation in all specific subsets of patients with spinal disease. The SF-6D is used commonly in analyses evaluating value in healthcare,¹²⁻¹⁴ an increasingly important aspect of outcome measurement, as it can be used to derive a utility score, the concept of which is discussed below.

The SF-6D is not the only proprietary instrument that can be used to measure general health and function. The EuroQol Group is a consortium of European researchers who developed a questionnaire designed to measure overall health and function, an instrument that is widely used in studying cost-effectiveness across all types of illnesses.

This instrument, known as the EQ-5D, was initially validated in England, The Netherlands, and Sweden, providing nearly identical results in each study site that led to rapid and widespread adoption in Europe.^{15,16} Although this questionnaire has been validated in the United States population as well, adoption in the United States has been slower, likely due to the availability of the domestically developed SF-6D. The EQ-5D questionnaire is composed of five questions, which were based on surveys about health perceptions completed by lay people and which cover different areas of human well-being—mobility, self-care, activities of daily living, pain, and anxiety/depression. Responses are divided into three states of relative function with the domain in question (no problems, some problems, and extreme problems) allowing for a total of 243 distinct health states. The EQ-5D is proprietary and is commonly used in cost-benefit studies,¹⁷⁻²¹ but requires purchase of a license to use the questionnaire from the EuroQol Group, which is based in Rotterdam, The Netherlands. While some researchers have described similar responsiveness of the EQ-5D and the SF-6D to changes in health state, this is not universally accepted.²²⁻²⁵ In addition to noting that neither questionnaire was validated in a language other than English, a recent review of the use of outcome measures in patients with low back pain suggested that either the EQ-5D or SF-6D questionnaire could be used with no particular advantage or disadvantage of either.²⁶

Disease-specific Outcome Measures

Disease-specific outcome measures focus on topics thought to be important to the spine. In this regard, these instruments may more specifically capture changes in health status related to treatments intended to decrease spine-associated pain or disability while avoiding confounding of outcomes by changes in nonspine health status or non-spine treatments. One major limitation of disease-specific instruments in the setting of increasing importance of CEA is that these instruments cannot be used directly to compare across unrelated diseases, although some spine researchers have tried to develop techniques to convert spine-specific measures into metrics used for CEA as described below in discussions of specific disease-specific outcome measures.

The Oswestry Disability Index (ODI) was developed in England to measure functional limitations associated with low back pain and is easy to use and score.²⁷ The answers for each question are assigned between 0 and

5 or 1 and 6 points depending on the version and simply added to determine the composite score. The composite score is then divided by the maximum possible score (a very useful feature in the case when a patient neglects or chooses not to answer one or more questions)—higher percentages indicate more severe disability. The questionnaire includes questions about functional abilities, activities of daily living, and social life. Since the original questionnaire was first published in 1980, the wording has been modified several times and the ODI has been translated into many languages, although it is not validated in all languages in which it is available. The version currently endorsed by the Musculoskeletal Outcomes Data Evaluation and Management System (MODEMS) initiative and supported by the American Academy of Orthopaedic Surgeons is a modified version containing fewer questions, precluding the use of raw scores instead of the percentage technique described above. The ODI has been widely validated in numerous versions.²⁸ Although there is little evidence that certain versions are substantially more or less valid than other versions, it is important to use only one version within a single multicenter study as subtle variation in scores may occur. Lastly, recent work to develop a method of converting ODI scores to SF-6D scores would increase the usefulness of this outcome measure and allow its incorporation into cost-effectiveness studies,²⁹ although dedicated CEA may benefit from the use of outcome measures intended for this purpose instead of relying on a conversion factor.

The Neck Disability Index (NDI) was developed as a cervical counterpart to the ODI and focuses on cervical spine symptoms and associated limitations. The scale is composed of 10 sections, with five general function sections directly borrowed from the ODI and the remaining five derived by an expert panel who sought to characterize and describe functional limitations related to the cervical spine. Similar to the ODI, each question has six possible answers and scores from each question are simply summed to determine the total score. The NDI has been shown to be reliable and valid^{30,31} and, similar to the ODI, Carreon et al. have developed a methodology to convert NDI responses into SF-6D scores to allow use in cost-effectiveness studies,³² although it has rarely been utilized for this purpose outside of this initial description.

The Zurich Claudication scale is a highly specialized instrument designed not only to apply to a specific part of the spine but also to a particular disease process, lumbar spinal stenosis.³³ This scale measures symptom severity,

functional limitations, and is often used to gauge post-operative satisfaction by focusing specifically on symptoms associated with spinal stenosis such as sciatica and leg strength in relationship to walking. The original description of this outcome instrument acknowledged that it was designed to be used in conjunction with other general health measures to gauge overall function, underscoring one of the weaknesses of such a uniquely specialized outcome measure. There has been no effort to develop a conversion of this scale to a general health measure.

The Japanese Orthopaedic Association (JOA) scale for myelopathy [officially known as the Japanese Orthopaedic Association Cervical Myelopathy Evaluation Questionnaire (JOACMEQ)]³⁴ and subsequently described modified JOA (mJOA) is another spine region and disease-specific instrument. This questionnaire has four sections, which qualifies limitations related to hand function, walking and stair climbing, upper extremity sensation, and micturition. The Benzel modification is the most widely used mJOA scale, which not only translated the questionnaire into English, but also removed culture-specific references from the original version such as descriptions of relative ability to use chopsticks, which would not be relevant for assessment of functional limitations in a western country.³⁵ The mJOA scale is strictly functional as it leaves little room for patients to subjectively assess the magnitude of their disability, instead emphasizing strict objective descriptions of the degree of loss of function.

■ UTILITY MEASURES

The concept of utility measurements is based on the idea that an individual's perception of his/her own health at any time can be represented by a point on a continuous health spectrum along a line from 0 to 1 with a higher score indicating that the individual is healthier. The extremes are defined by 1 = perfect health for 1 year and 0 = death. The utility measure scale is meant to be identical across all diseases meaning that two disease states with the same utility score are equally undesirable, although likely in different ways. Furthermore, utility scores are the ultimate general health instrument as they consider the sum effect of all medical and psychological illnesses that an individual has without any distinction as to the relative contributions of each disease to the overall score.

Direct determination of utility associated with a health state is most often calculated in one of two ways: the standard reference gamble method or the time trade-off method.

The gamble method evaluates a patient's willingness to accept a particular health state and is instructive in explaining how a single scale can be used to compare all health states. This method establishes a probability P at which an individual is indifferent between (1) entering into a gamble where he/she would have either perfect health with the probability P or death with probability $(1 - P)$ and (2) living with the disease state in question. The value of P also represents the utility measure for that disease state. Health states with considerable disability would encourage the individual to accept a lower likelihood of perfect health and a higher chance of death before he/she would become indifferent, leading to a lower utility score for more disabling conditions. While interesting conceptually, the gamble method has obvious limitations in terms of being relatively abstract and impractical as a technique to establish utility scores in a research study setting. Fortunately, as described above, several questionnaire instruments have been designed and validated to yield utility measures with relatively short and efficient questionnaires including the SF-6D and the EQ-5D. These are considered indirect albeit validated techniques to determine utility, which do not use either direct method mentioned above.

The SF-6D is composed of SF-36 questions that evaluate physical functioning, role limitations, social functioning, pain, mental health, and vitality with approximately 18,000 total possible health states based on the five choices for each of six questions. Instead of the two subscores that the SF-36 provides, the SF-6D yields a single utility score that can be used for cost-effectiveness studies. Numerous studies have been performed to compare utility scores derived from the SF-6D and the EQ-5D, the two most commonly used utility score instruments, in many different patient populations³⁶⁻⁴⁰ often leading to suggestions that the two utility questionnaires lead to widely variable utility scores. There is little guidance that one instrument is superior to the other, but these findings raise some concerns about the accuracy of CEA, especially given the often uncertain nature of the cost calculations, which makes up the other important input aside from the utility scores. Within the field of spinal disease, comparisons of utility scores from EQ-5D and SF-6D have similarly identified wide variation in scores, suggesting utility scores calculated from one or the other instrument should not be pooled together in a single study or compared with one another for patients with chronic low back pain⁴¹ or a variety of degenerative lumbar conditions including disc herniation, spinal stenosis, or spondylolisthesis.⁴² Without a gold

standard such as the gamble or time trade-off method performed concurrently, there is no basis for guidance as to whether the SF-6D or EQ-5D has greater accuracy.

UTILITY SCORES FOR SPINAL AND NONSPINAL PATHOLOGY

Reported utility scores for spine patients in cost-effectiveness studies of spinal surgery vary from 0.35 to 0.79,^{14,19-21,43,44} as described above, substantial variation as high as 0.18 was reported depending on which questionnaire (EQ-5D or SF-6D) and version (US vs. UK) was used.²¹ In a study comparing utility between orthopedic patients with a wide variety of problems, the baseline utility of patients with spinal pathology was substantially worse (lower score) than were the utility scores for patients with severe arthritis of the hip, knee, or ankle.⁴⁵ Interestingly, improvement in utility after surgery was greatest for spinal stenosis patients treated with decompression surgery even when in comparison to the improvements shown by patients who underwent total hip and total knee arthroplasty, operations that are widely considered as examples of the most successful surgeries invented in any field of modern medicine. A recent systematic review of the use of cost-utility analysis to study treatment of chronic low back pain described an average preoperative utility of 0.59 across 15 different studies of low back pain, which reported either utility scores or outcome measures that could be converted into utility scores on a post hoc basis.⁴⁶ This provides compelling insight into the difficulties faced by this challenging patient population as recent publications describing utility scores associated with other chronic medical conditions have reported 0.73 for morbid obesity,⁴⁷ 0.7 for type II diabetes,⁴⁸ 0.77 for dialysis patients who perform home peritoneal dialysis,⁴⁹ 0.53 for patients who are treated with traditional hemodialysis,⁴⁹ and 0.64 for moderately severe congestive heart failure.⁵⁰ Spine surgeons should welcome the arrival of CEA-based research due to the great improvement in utility scores associated with well-indicated spine surgery and the low baseline utility scores and associated great potential for improvement in patients with untreated spinal disease.

QUALITY-ASSOCIATED LIFE YEAR

The quality-associated life year (QALY) incorporates the concept of utility and the length of time that a particular health state will last to simultaneously consider quality and quantity of life by multiplying utility and the duration

it lasts. Because perfect health (utility = 1) for 1 year will result in a product of 1 (1.0 utility score \times 1 year = 1), the product of any given utility score and the length of time a health state lasts will give the number of years of perfect health equivalent to living for the utility score in question for that particular length of time. The QALY, therefore, is expressed in units of perfect health for 1 year, allowing comparison across disparate health states with different magnitudes and types of associated disability. From a practical standpoint, QALY calculations typically use average utility measures from indirect outcome instruments such as the EQ-5D or the SF-6D (as opposed to the gamble or time trade-off method) and estimates of the length of time a treatment benefit will last or actuarial data on life expectancy when treatments are expected to change health status permanently.

The QALY data is integrated into cost-effectiveness studies by calculating average change in utility from pre-intervention to final follow-up, which can be attributed to whatever treatment is rendered. The total cost of treatment is divided by the overall change in QALY to provide a cost/QALY that can be compared across different treatments to describe the relative cost-effectiveness of one treatment compared to another. Although it is less intuitive, this number can theoretically be negative due to a negative change in utility—this could either identify a bad treatment that led to a worse health state or may simply describe an effective treatment that slowed the decline in utility in a progressively disabling disease.

Accurate cost calculation is commonly the most difficult and controversial aspect of cost-utility analysis due to lack of cost transparency in many healthcare systems and the complexity of assigning and tracking the indirect costs of treatment. For spine surgery, direct costs include the cost of any instrumentation used, operating room time, surgeon, and anesthesia fees, costs of subsequent hospitalization, imaging, and rehabilitation as well as the cost of complications or treatment failures such as revision surgery. Indirect costs are more difficult to accurately capture and include decreases in productivity/work associated with postoperative recovery and lost productivity of family members who must care for the patient. Additionally, because patients with severe spinal pathology treated nonoperatively often accrue significant costs associated with narcotic analgesics and missing work, avoidance of such expenses may be important to include if surgery results in substantial cost savings. Dividing the cost of surgical intervention including both direct and

indirect costs by the total lifetime QALY gained through the surgery provides a measure of cost per year of perfect health gained and is the basis for comparative analysis between different treatments.

Many cost researchers have adopted the method described above to report QALYs because it is straightforward and there is an intuitive interpretation of the metric. Some authors, however, have objected to the process of multiplying a utility measure and time period to obtain a meaningful quantity. Indeed, this multiplicative model may not match with empiric data in all cases and there are many scenarios in which this measure of cost utility cannot be applied.^{51,52} For instance, QALY is difficult to apply to acute conditions where treatment will lessen pain but ultimately not change the otherwise expected outcome—for example, epidural anesthesia during childbirth compared to natural childbirth cannot be accurately assessed because pain during childbirth is not a persistent state for which a representative utility could be assigned nor could questionnaires realistically be completed during the short window when patients occupy this “health state.” Aggregating utility measures for the purposes of determining “average” improvements in utility associated with treatment also have theoretic disadvantages for decision-making. Strict evaluation of treatment by average QALY, for example, would favor treatment using a therapy which kills half of the patients but restores half to perfect health compared to a second, identical-cost treatment which kept both patients alive but at a utility score of 0.49. This QALY preference is unlikely to be reflected by preferences of individual patients requiring treatment.⁵² Hence, an underlying criticism of QALY is that it is not individualized enough to weigh the health and time preferences and risk appetite of the individual who will undergo treatment.⁵³ Alternate methods to quantify treatment value have been proposed whose proponents claim to overcome these limitations such as healthy-year equivalent (HYE), but have not gained traction or widespread adoption in spinal surgery cost-effectiveness studies. The HYE uses a two-step interview process similar to the gamble method described above with separate scenarios to gauge quality and time considerations to determine utility.⁵⁴ Such research methodology would require substantial financial and personnel resources. In contrast, the QALY can be derived from the SF-6D and the EQ-5D, widely known and well-accepted self-administered instruments. As described above, efforts to derive utility scores from disease-specific outcome measures have been undertaken by Carreon et al. to provide techniques so

that the NDI³² and ODI²⁹ can be used for CEA, potentially encouraging more researchers to engage in cost-effectiveness research using a QALY approach. Until an alternative is developed that is simple and quick to administer, the QALY will likely remain the standard metric for cost-effectiveness studies in spinal surgery despite the limitations outlined above.

The preceding description of CEA highlights the increasing importance of cost in the measurement of outcomes after spinal surgery. While the denominator of the cost/QALY ratio may be favorable for some aspects of spinal surgery due to the related baseline disability and successful nature of well-indicated surgical intervention, spine surgery remains very expensive due largely to the high cost of spinal implants. As cost and measurement of outcomes become inseparable and potentially linked to reimbursement, spine surgeons will face greater pressures to help control implant costs, potentially through hospital commitments to a single manufacturer or through judicious use of less expensive implants. A second consequence of the high cost of spinal implants is that the cost structure associated with spinal surgery is heavily front-loaded. Treatments with front-loaded cost structures have a disadvantage in demonstrating cost effectiveness as improvement in utility becomes greater with longer follow-up because the upfront cost is spread over a greater time period. High rates of patient follow-up at such long time points is difficult to achieve.

KEY POINTS

- Reflecting a trend in the practice of medicine in general, spine surgery is moving rapidly toward patient-centered outcome measures and away from surgeon-reported outcome measures.
- The collection of process measures is simple to do and often does not require a major data collection effort, but may not accurately reflect the quality of care delivered.
- General health outcome instruments have the advantage of being comparable across different disease states, but may be less responsive to treatment of spinal disease, while disease-specific outcome instruments should be more responsive to treatment of spinal disease, but are less useful for comparisons between patients with different diseases, an important component when performing CEA.
- A utility score is a number between 0 and 1, which captures the overall health status of a patient; changes

in utility scores are used in CEA to identify the cost of an intervention relative to the change in utility associated with that treatment.

- Cost-effective analysis will become increasingly important to allocate healthcare spending if the cost of healthcare continues to escalate. Longer follow-up is important for cost-effectiveness research in spine surgery because of the high upfront costs and durable benefit to the patient.

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Glassman SD, Polly DW, Dimar JR, et al. The cost effectiveness of single-level instrumented posterolateral lumbar fusion at five years after surgery. *Spine (Phila Pa 1976)*. 2012;37(9):769-74.

This is an example of a well-performed CEA study with 5 years of follow-up, which demonstrates how this research is performed and the lasting benefit to spine surgery that will continue to drive down the cost/year as longer follow-up periods are employed.

Carreon LY, Glassman SD, McDonough CM, et al. Predicting SF-6D utility scores from the Oswestry disability index and numeric rating scales for back and leg pain. *Spine (Phila Pa 1976)*. 2009;34:2085-9.

This study represents an important step in utilization of disease-specific outcome measures for cost-effectiveness analysis via conversion of the ODI to a utility score.

Carreon LY, Anderson PA, McDonough CM, et al. Predicting SF-6D utility scores from the Neck Disability Index and numeric rating scales for neck and arm pain. *Spine (Phila Pa 1976)*. 2011;36(6):490-4.

This study represents an important step in utilization of disease-specific outcome measures for cost-effectiveness analysis via conversion of the NDI to a utility score.

McDonough CM, Grove MR, Tosteson TD, et al. Comparison of EQ-5D, HUI, and SF-36-derived societal health state values among Spine Patient Outcomes Research Trial (SPORT) participants. *Qual Life Res*. 2005;14:1321-32.

This subanalysis of SPORT demonstrates the possibility for divergence of CEA data if different methods of calculating utility scores are used and is a cautionary tale against comparing utility derived using different techniques.

Duru G, Auray JP, Beresniak A, et al. Limitations of the methods used for calculating quality-adjusted life-year values. *Pharmacoeconomics*. 2002;20:463-73.

This paper provides interesting insight into the limitations of the QALY and introduces important considerations for healthcare researchers interested in CEA.

Outpatient Rehabilitation of Lumbar Spine Disorders

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Snapshot

- » History
- » Differential Diagnosis

- » Treatment

HISTORY

A thorough history and physical examination is the cornerstone of diagnosis in the patient with low back pain. Without a thorough clinical evaluation, it is difficult to interpret an anatomic study. Furthermore, the history and physical examination is essential for the development of a treatment plan.

History should include location of back pain, leg pain, and paresthesia, as well as, character, severity, timing (onset, duration, frequency), alleviating and aggravating factors. Pain that is worsened by standing and walking may indicate central spinal stenosis, while pain that is worse with sitting is more consistent with discogenic pain. Progressive weakness or bowel or bladder incontinence may lead to urgent surgical intervention. Previous treatment and medication strategies as well as whether or not they were successful must be investigated in order to determine future treatment options.

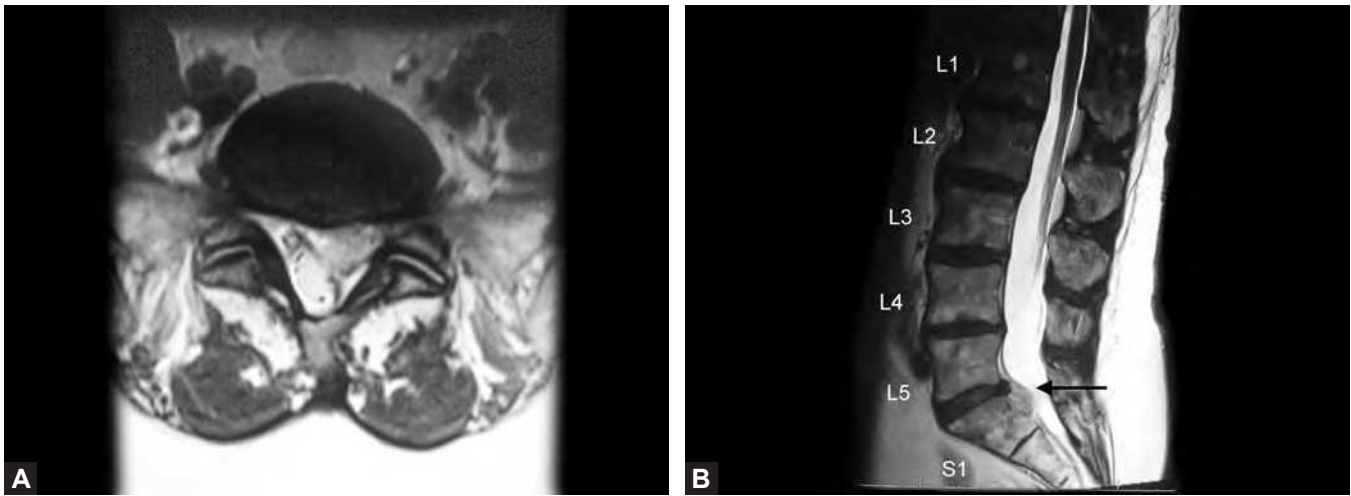
Previous history of malignancy, age over 50, ongoing pain of more than 1 month duration, failure to progress with conservative therapy, high sedimentation rate and anemia may raise questions of underlying cancer.¹ History of infection and rheumatologic disease should be noted. Psychological evaluation is also useful in determining prognosis. Factors such as poor job satisfaction, depression, catastrophic thinking, and excessive downtime may predispose to disability.²

Physical examination of the lumbar spine should include inspection, palpation, range of motion, motor, sensory, and reflex examination, provocative maneuvers, and observation of ambulation. Evaluation begins when the practitioner meets the patient. Observation of sitting posture, transfer from a seated to a standing position, as well as gait stability are important. Gait deviations such as steppage gait or compensated Trendelenburg gait may point toward specific areas of weakness or structural deviation of the hip or ankle.

In the anterior plane, asymmetry in shoulder, iliac crest, greater trochanter, and patellar height should be assessed. In the posterior plane, scapular symmetry, scoliosis, posterior superior iliac spine, gluteal folds, popliteal creases, and medial malleolus should be assessed. In the lateral plane, a loss of lordosis or hyperlordosis should be assessed. An increased lumbar lordosis may be a sign of a spondylolisthesis. A loss of lumbar lordosis may indicate acute low back pain with associated muscle spasm. Skin lesions, erythema, ecchymosis, previous surgical sites, or muscle atrophy should be noted.

Palpation of the spinous and transverse processes, iliac crest, greater trochanters, and sciatic notch should be assessed in both the standing and prone positions. Tender points and taut bands can be noted in the lumbar paraspinals, piriformis, gluteals, and tensor fascia lata.

Leg length discrepancy should be evaluated by measuring from the anterior superior iliac spine and umbilicus to the medial malleoli. Motion of the lumbar spine should



Figs. 16.1A and B: Axial and sagittal image of a patient without any pain in spite of a large left-sided intervertebral disc herniation at L5-S1.

be assessed in flexion, extension, side bending, and rotation. Hip and knee range of motion as well as flexibility of the hamstrings, tensor fascia lata, and gastrocnemius mechanism should be evaluated.

The straight leg raise is performed with the patient in the supine position. The examiner passively raises the patient's leg with knee in extension. Pain produced in the posterior leg below the knee between 30° and 70° indicates a positive test, compatible with radicular pain. Crossed straight leg raise results in discomfort in the painful extremity by elevating the contralateral extremity. The slump test is performed when the seated patient flexes his/her chin to the chest. The examiner passively extends the patient's knee and dorsiflexes the foot. In the patient with a radiculopathy, pain radiates down the affected extremity. Femoral nerve test, also known as reverse straight leg raise, causes pain by stretching the femoral nerve in a patient with an upper disc herniation. With the patient in a prone position, the examiner flexes the knee to 90° and then extends the hip, which results in pain radiation into the anterior thigh.

Radiologic evaluation should be interpreted in the context of the clinical picture. Approximately, 30% of patients have discogenic changes in the absence of clinical complaints; this percentage increases with age.³ Conversely, patients may have changes that are impressive to view, but not correlate with clinical presentation (Figs. 16.1A and B).

Conventional X-rays are widely available, easy to obtain, inexpensive, and may provide a good initial screening tool. X-rays can provide information regarding spinal alignment (spondylolisthesis), degenerative changes (disc space

narrowing, osteophytes, and endplate sclerosis), fractures (pars fracture or spondylolysis), vertebral fractures, and cortical bone destruction (neoplastic or inflammatory process). They do not need to be performed routinely and their main utility is an initial evaluation for fracture, malignancy, infection, and instability.

Magnetic resonance imaging (MRI) has superior contrast resolution, which allows for better visualization of soft tissue, nerve roots, disks, vertebrae, spinal cord, and cerebrospinal fluid. It is the best study for looking at the intervertebral disk. It should be ordered with progressive neurologic deficit, unclear diagnosis, concern over malignancy or fracture, and if interventions such as spinal injections or surgery are being contemplated. Magnetic resonance imaging with contrast (gadolinium) allows for better detection of inflammatory processes, tumors, or delineation of recurrent intervertebral disc herniation versus scar tissue in patients who have previously undergone spinal surgery. Disadvantages to MRI are cost, claustrophobia, and contraindications to obtaining an MRI such as pacemakers or other metal implants.

Computed tomography (CT) provides high resolution detail of bony architecture. Computed tomography better evaluates fractures, facet joints, central or foraminal stenosis, and osseous tumors. It is less expensive than MRI and may be used in patients who have contraindications to MRI. It is less sensitive than MRI in detecting infection, tumor, disc herniations, or spinal cord pathology.

Myelography and postmyelography CT is utilized in patients who have contraindications to obtaining an MRI if further evaluation of the intervertebral disc and

neurologic elements is warranted. Patients who have had instrumentation that interferes with the MRI might also require myelography if a surgical procedure for radicular symptoms is being contemplated.

■ DIFFERENTIAL DIAGNOSIS

Axial pain differential diagnosis includes osseous pathology, myofascial pain, facet and sacroiliac joint dysfunction, discogenic and visceral pain. Radiating pain differential diagnosis includes radiculopathy, sacroiliac joint, facet joint pain, and peripheral nerve lesions. Pelvic and long bone fractures, as well as hip and knee joint pathology can also be responsible for lower extremity pain.

Another organizational option is to place patients with low back pain into one of three categories: nonspecific low back pain, back pain potentially associated with radiculopathy or spinal stenosis, or back pain associated with another specific spinal cause (malignancy, fracture, infection, etc.). This is less specific, but may be a more practical initial approach for the patient with lumbar pain. More specific evaluation for the pain generator may take place depending on the individual's progress.⁴

■ TREATMENT

Lifestyle

Obesity is associated but not causative of lower back pain. Patients with chronic spinal disorders are at higher risk for obesity secondary to inactivity, depression, and utilization of medication, which may lead to weight gain. Morbidity associated with obesity includes cardiovascular disease, gallbladder disease, and breast cancer. Obesity results in less optimal outcomes with nonoperative management of degenerative spondylolisthesis and intervertebral disc herniations.^{5,6}

Tobacco has a weak association with lower back pain. Vasoconstriction of vasculature, ischemia, and coughing may result in increased lower back pain related to smoking. There is also an increased risk of nonunion with lumbar fusion secondary to nicotine exposure.⁵

Medication

Nonsteroidal anti-inflammatory drugs (NSAIDs), corticosteroids, muscle relaxants, opioids, antidepressants, and antiseizure medication have been utilized in the treatment of spinal conditions. Medications should be utilized based on

their risk-benefit ratio. Medication that does not provide benefit after a reasonable trial should be discontinued.

Acetaminophen and NSAIDs are usually first-line treatments for spinal pain. They are usually classified together despite the fact that acetaminophen has little, if any, anti-inflammatory effect. These agents are inexpensive and have a well-known adverse reaction profile.⁷ Chou et al. attribute moderate short-term benefits to these agents.⁸

Nonsteroidal anti-inflammatory drugs work by the inhibition of prostaglandin synthesis at the cyclooxygenase receptors. Nonselective NSAIDs block both COX-1 and COX-2 receptors and have both analgesic and anti-inflammatory effects. Known adverse reactions to NSAIDs include potential renal, cardiovascular, and gastrointestinal bleeding. COX-2 selective NSAIDs such as celecoxib are equally effective to other NSAIDs regarding pain relief with less gastrointestinal toxicity and platelet effect.

Corticosteroids have been used to treat spinal pain with limited benefit. There has been anecdotal efficacy in radicular symptoms, first documented in 1970.⁹ Conversely, there have been no randomized clinical trials that prove efficacy of oral corticosteroids in either axial or radicular pain.¹⁰

Opioid analgesics are commonly prescribed for severe acute and chronic spinal pain. They may be considered a second-tier treatment for pain that is not controlled by NSAIDs, acetaminophen, or other nonpharmacologic means. The use of opioids has increased dramatically in the treatment of nonmalignant pain. Unfortunately, the increased volume of opioid prescriptions has corresponded to simultaneous problems of misuse, addiction, and illegal drug diversion. Adverse effects of opioids include somnolence, nausea, vomiting, constipation, respiratory suppression, and addiction. The risk of addiction has been estimated at <5%.¹¹⁻¹⁵

Tramadol is a weak synthetic opioid that also prevents reuptake of serotonin and norepinephrine as its mechanism of action. Because it is a weak opioid, there is less potential for addiction than traditional opioids. Common adverse effects with tramadol include nausea, vomiting, somnolence, headaches, and constipation. Tramadol, when combined with antidepressants with selective serotonin reuptake inhibitor (SSRI) or selective norepinephrine reuptake inhibitor (SNRI) mechanisms, lowers the seizure threshold.

Tricyclic antidepressants have been prescribed in chronic pain patients with depression and these patients had improvement in their pain symptoms. The dosages prescribed for analgesia are less than those used in treat-

ment of depression. Three classes of antidepressants are generally used to treat pain. They are tricyclic antidepressants, SSRIs, and SNRIs. The older tricyclic agents can be very effective for pain and sleep, but are notorious for side effects such as sedation, cardiac arrhythmia, constipation, urinary retention, dry mouth, and weight gain. Selective norepinephrine reuptake inhibitor, the newest class of antidepressants used in treatment of pain, includes duloxetine, which has been approved for treatment of chronic musculoskeletal pain.

Anticonvulsant medications such as gabapentin and pregabalin have been commonly prescribed for neuropathic pain in patients with radiculopathy. The general mechanism of these agents involves inhibition of calcium and sodium channels to decrease glutamate and increase gaba aminobutyric acid (GABA) in the central nervous system. Analgesia occurs by the stabilization of neural membranes. Side effects include dizziness, somnolence, fatigue, headache, swelling, nausea, weight gain, possible rebound seizures, and suicidal ideation.

Other medications that are used for spinal pain and/or radiculopathy include topical agents such as NSAID patches (diclofenac) or topical anesthetics (lidocaine). Counterirritant topical agents such as capsaicin may provide local relief. Antispasmodics such as baclofen, tizanidine, or medication for muscle “spasm” such as metaxalone may be used for axial lumbar pain.

Rehabilitation

The rehabilitation of patients with spinal pain requires a good understanding of the anatomy, biomechanics, and function of the axial skeleton. Although many cases of spinal pain are self-limiting, proper rehabilitation is necessary to reduce the high incidence of recurrence and to facilitate an independent return to preinjury activities and prevent future disability. A successful rehabilitation program is multifaceted and focuses on correcting an individual's biomechanical abnormalities with the use of a structured exercise program. Education on posture and proper body mechanics will also help prevent further injury and pain. It is important to note that the goal of a rehabilitation program for patients with chronic spinal pain is to maximize function and facilitate independent management of the condition even with an ongoing impairment. Due to the complexities of the biopsychosocial model of spinal pain,¹⁶ an interdisciplinary approach may be the best way to prevent long-term disability in patients with certain risk factors.

Stability of the spine is achieved both passively and

actively. The intervertebral disk, zygapophyseal joints (z-joints), ligaments, and muscles contribute to spinal segmental stability. There are numerous muscles in the spine that act to provide dynamic stability and generate motion. In general, the shorter spinal muscles act as segmental stabilizers, while the longer muscles act as prime movers. Proper biomechanics and function of the spine is dependent on a balance between anterior and posterior muscle activity. Alterations in this balance can lead to abnormal postures and excessive force on various structures in the spine.

In the lumbar spine, prolonged sitting and/or repetitive bending and lifting can lead to abnormal lumbopelvic mechanics and posture. Prolonged sitting with coexposure to whole body vibration and/or awkward postures has been shown to increase the risk of low back pain four-fold.¹⁷ Most postural changes occur gradually over time, allowing for tissues to accommodate without symptom manifestation.

It is usually after a traumatic event (i.e. whiplash or lifting injury) that symptoms arise. In the acute phase, relative rest and protecting the injured tissues will help in pain management. Controlling inflammation and early mobilization of the spine can help prevent atrophy of the spinal muscles and prepare the patient for a therapeutic exercise program. In a comprehensive rehabilitation program, normal trunk and lower extremity strength, endurance, and power should be combined with education and training for posture, body mechanics, and proprioception to allow successful and sustained return to activity.

In acute back pain, the goal of exercise is to manage pain by initiating tolerable movement. In patients with radicular pain, centralization of symptoms is desired. However, numerous randomized, prospective studies and review papers have failed to demonstrate the benefit of exercise in acute low back pain.^{18,19} When direction of movement is selected based on symptoms, more positive results can be demonstrated from an exercise intervention.^{20,21} In patients with posterior disc herniations, extension exercises may be effective in changing intradiscal pressure,²² allowing anterior migration of the nucleus pulposus²³ and decreasing tension on the nerve root. Flexion-based exercises may be more effective in treating zygapophyseal joint pain and spinal stenosis in the lumbar spine by decreasing compressive joint forces.

As the acute pain subsides, the goal is to progress to spinal stabilization or “core strengthening” exercises in order to improve function and decrease the chance of future recurrence of pain. In the lumbar spine, the develop-

ment of a muscular corset, including the rectus abdominus, multifidi, and various pelvic and trunk muscles that attach to the thoracolumbar fascia, can decrease shearing forces across the three-joint complex. Once proper muscle lengthening has occurred, it is possible to strengthen the inhibited muscles via neuromuscular reeducation and closed kinetic chain exercises.²⁴ Initial core strengthening exercises are usually done in the neutral spine position with the pelvis at the midpoint of anterior and posterior tilt, the scapulae midway between protraction and retraction, and the head in the same coronal plane as the shoulders. This decreases tension on the ligaments and joints of the spine and is usually the position of greatest comfort. The next step is to strengthen the prime movers of the spine as well as the extremities while keeping the neutral spine position, which will facilitate neuromuscular coordination. Advancement to dynamic multiplanar strengthening exercises will help in preparation for return to normal functional activities.

A majority of the literature on exercise therapy in treating spinal pain has looked at patients with “nonspecific” low back pain. The ambiguity of this term is evident and serves as one of the major potential limitations in this large group of research articles and review papers. In addition, therapeutic exercise programs come in many forms and are often coupled with multiple cointerventions. Because of the heterogeneity of both exercise treatment options and patient populations, the level of evidence is low. A 2005 Cochrane review of exercise therapy for treatment of nonspecific low back pain concluded that exercise therapy appears to be slightly effective at preventing recurrences, decreasing pain, and improving function in adults with chronic low back pain, but that it is as effective as either no treatment or other conservative treatments in patients with acute low back pain.²⁵ In a more recent review article on nonsurgical care of chronic low back pain, Standaert et al. found low-level evidence that structured exercise improved pain and function within 8 weeks of care, but that it was no more effective than spinal manipulative therapy (SMT).²⁶ Since that review article, a randomized controlled trial with long-term follow-up showed the added benefit of an exercise program with ergonomics training and back school compared to passive therapy in nurses with chronic low back pain (Fig. 16.2).²⁷

Prolotherapy is the injection of an irritant (proliferant) solution into ligaments and tendons for treatment of chronic musculoskeletal pain. Its mechanism of action is the reduction of joint instability through the strengthening of stretched or torn ligaments. This is thought to occur

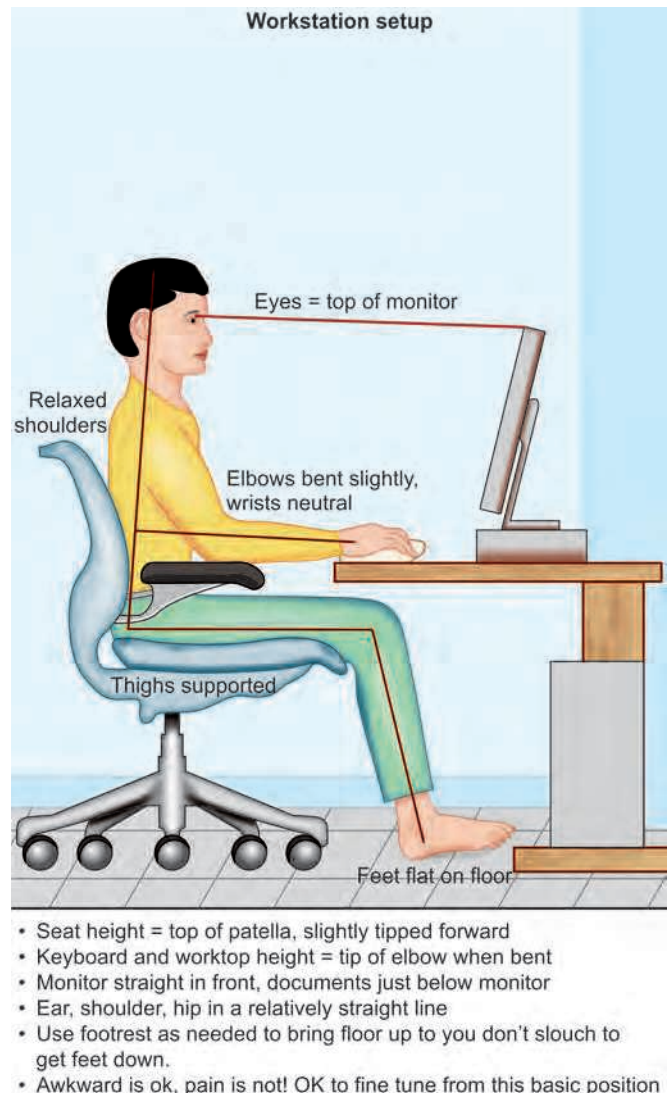


Fig. 16.2: Proper ergonomic positioning for seating at a desk.

through the release of granulocytes, macrophages, fibroblasts, and growth factors, leading to collagen deposition, thereby strengthening ligaments.²⁸ This may reduce pain and improve overall flexibility and function.

Proliferant solutions are classified into three groups: irritants, chemotactics, and osmotics. Irritants include phenol, guaiacol, tannic acid, and pumice flour. The only chemotactic solution is sodium morrhuate. Osmotics include concentrated solutions of glucose, glycerin, and zinc sulfate.²⁸ A local anesthetic is often added to reduce postinjection pain. Hyperosmolar dextrose appears to be the most commonly used agent today, with sodium morrhuate used slightly less often. Prolotherapy alone has not been proven to be beneficial in the treatment of lower back pain.

However, in the presence of cointerventions, prolotherapy may be more beneficial than control injections alone.²⁹

Traditional Chinese acupuncture is based on ancient beliefs regarding the flow of vital energy, known as *qi*, through the body along pathways termed meridians. Blockage of *qi* is thought to be manifested as tenderness on palpation. Specific points along these meridians are penetrated using fine solid metallic needles to balance the energy flows within the body. Although many different styles of acupuncture have developed over time as its use has spread into other cultures, the traditional Chinese approach appears to be the most widely practiced in the United States.³⁰ Acupuncture has been shown to induce the release of endogenous opioids in brainstem, subcortical, and limbic structures. Functional MRI and positron emission tomography have shown that acupuncture stimulates regions of the brain involved in pain processing, as well as increases opioid binding potential in these same regions. Acupuncture also has effects on local tissues, including mechanical stimulation of connective tissue, release of adenosine at the site of needle stimulation, and increases in local blood flow.³⁰ Adverse side effects, while rare, may include needle site pain, bleeding, nausea, vomiting, dizziness, and fainting.

Several clinical studies have evaluated the effectiveness of acupuncture for chronic lower back pain (LBP). In a recent meta-analysis of 6,359 patients, Yuan et al. concluded that there is no significant difference between acupuncture and sham acupuncture (superficial needle insertion at nonacupoints), for short-term and intermediate pain relief and functional improvement.³¹ However, based on their analysis, they did advocate the use of acupuncture for chronic LBP. Recently, the North American Spine Society has also concluded that acupuncture provides better short-term pain relief and functional improvement than no treatment and that the addition of acupuncture to other treatments provides a greater benefit than other treatments alone.³¹

Spinal manipulative therapy is a frequently applied treatment for back and neck pain. It includes a range of manual therapy techniques applied to the spine; however, the most common usage relates to high velocity low amplitude procedures. Here the practitioner applies a rapid thrust, producing joint cavitation that is often accompanied by an audible “pop.” Articulations in the lumbar spine that are amenable to SMT include the zygapophyseal, lumbosacral, and sacroiliac joints. The effects of spinal manipulation have been shown to include temporary relief of musculoskeletal pain, shortened time to recover from acute back pain, temporary increase in passive range of



Fig. 16.3: Patient in position to receive osteopathic manipulation for the lumbar spine.

motion, physiological effects on the central nervous system, and altered sensorimotor integration (Fig. 16.3).³²

While numerous studies have been conducted on the efficacy of SMT, there is limited evidence advocating its use in chronic LBP. In a 2011 Cochrane review of 26 randomized controlled trials, Rubinstein et al. concluded that there is no clinically relevant difference between SMT and other conventional interventions for reducing chronic lower back pain.³³ A meta-analysis by Shekelle et al. found moderate evidence that SMT has an effect similar to an efficacious prescription of NSAID.³⁴ In contrast, in cases of acute LBP, results from most studies suggest that SMT administered over 2–4 weeks achieves equivalent or superior improvement in pain and function when compared with other commonly used interventions.³⁵

Injection Options for Low Back Pain

Spinal injections for low back pain are utilized for diagnostic as well as therapeutic reasons. Injection options include interlaminar and transforaminal epidural steroid injections, lumbar zygapophyseal (z-Joint) procedures, and sacroiliac procedures. Spinal injections are generally performed with fluoroscopic guidance, although some can be performed with CT guidance. Image-guided approaches have demonstrated increased safety, efficacy, and reliability.³⁶

Contraindications to lumbar spinal injections include active infection, either locally or systemically, bleeding disorders, anticoagulation, uncontrolled hypertension, hyperglycemia, and injectate allergy.

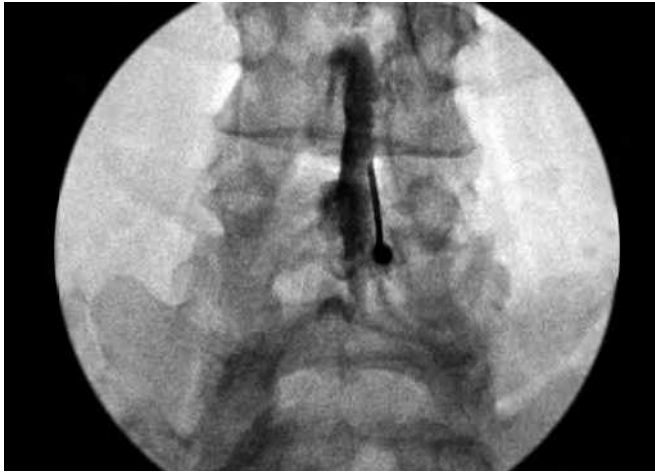


Fig. 16.4: Anteroposterior view of interlaminar epidural steroid injection at L3-L4 on right.

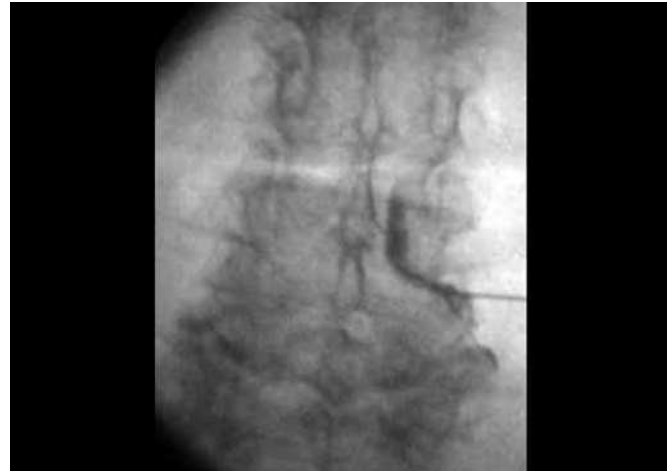


Fig. 16.5: Transforaminal injection at the right L4-L5 interspace.



Fig. 16.6: Left-sided z-joint injection.

Lumbar radiculitis and radiculopathy are the primary indications for epidural steroid injections. Epidural steroid injections have been found to be beneficial for the treatment of acute radiculopathies, especially for short-term outcomes in pain and function.³⁷⁻³⁹ Patients with a lesser degree of nerve root compression, who may have more of an inflammatory etiology for their pain, may respond better to transforaminal steroid injections than patients who have a higher degree of neurologic compression of the nerve root.⁴⁰ These injections may be beneficial in the relief of primarily disc mediated low back pain as well. There are two common approaches to lumbar epidural steroid injections. Interlaminar injections involve the placement of a Tuohy needle, using a loss-of-resistance technique, into the epidural space (Fig. 16.4). A transforaminal epidural injection involves placing the spinal needle

adjacent to the exiting nerve root as it leaves the spinal column (Fig. 16.5).⁴¹ The injectate is usually a combination of a long-acting steroid preparation with a local anesthetic. However, there is little evidence to suggest the addition of a local anesthetic in epidural steroid injections provides improved outcomes.⁴² Potential complications include bleeding, epidural hematoma, infection, epidural abscess, nerve injury, muscle weakness, increased pain, arachnoiditis, paralysis, meningitis, osteomyelitis, spinal headache, and avascular necrosis.³⁸

Adverse side effects of the steroid preparations include skin hypopigmentation, subcutaneous fat necrosis, skin flushing, hyperglycemia, insomnia, hiccups, and fluid retention. Repeated injections can lead to adrenal suppression and cushingoid appearance.

Selective nerve root injections are diagnostic procedures using a local anesthetic to block a spinal nerve suspected of causing associated lumbar radiculitis symptoms. The patient's response to the injection is followed and documented to determine the primary pain generator.

Lumbar z-joint and medial branch nerve block injections are used in diagnosing and treating facet-mediated pain. Symptomatic facet joints have a prevalence of 10-40% in chronic low back pain.^{43,44} Intra-articular injections consist of placing the needle within the joint and injecting the facet joint under fluoroscopic guidance. The medial branch block is done by injecting along the medial branch of the posterior primary ramus as it crosses over the posterior aspect of the transverse process. Pain alleviation from local anesthetic blockade of the medial branch block on two occasions confirms the z-joint as the pain generator. Radiofrequency ablation of the medial branches may provide long-term pain relief (Fig. 16.6).⁴⁵⁻⁴⁷



Fig. 16.7: Intra-articular injection of the left sacroiliac joint.

Sacroiliac joint pain has a reported prevalence of 10–25% of cases of axial low back pain. Sacroiliac joint injections with fluoroscopic guidance are the gold standard in diagnosis and treatment of sacroiliac joint-mediated pain. Steroid containing injections and radiofrequency denervation techniques can be used to provide long-term improvement. Complications include joint rupture and sciatic nerve injury (Fig. 16.7).⁴⁸

KEY POINTS

- Diagnostic studies need to be evaluated in light of the history and physical examination to arrive at a diagnosis and create a treatment plan.
- Medical conditions such as metastatic cancer, infection, and rheumatologic disease should be noted.
- Previous history of malignancy, age over 65, nocturnal pain, and significant weight loss may raise questions of underlying malignancy.
- The use of exercise to treat subacute and chronic lumbar pain is an essential part of treatment, although the evidence is not yet robust.
- Evidence supports that interlaminar and transforaminal epidural steroid injections provide short-term relief of radicular pain.

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SECTION

2

Developmental Disorders

Luiz R Vialle

Embryology of the Spine

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Snapshot

- » Embryologic Origin
- » Genetic Influence on Spinal Development
- » Development of the Vertebral Column
- » Development of the Spinal Cord
- » Postnatal Maturation of the Spine
- » Congenital Malformations of the Spine
- » Failure of Spine Development

INTRODUCTION

One of the least understood disciplines in embryology is the development and the pathogenesis of congenital spinal abnormalities. The spine's development into multiple, highly specialized subunits is very sophisticated and not completely understood. Recent advances in genetic laboratory techniques have greatly contributed to our understanding of cell signaling, gene silencing, gene expression, and the pathological disorders.

EMBRYOLOGIC ORIGIN

The process in which a bilaminar disc becomes a trilaminar disc marks the earliest development of the spine, a process called gastrulation.¹ By week 3, the notochord and somites form through molecular signaling from the ectoderm of the trilaminar disk.² Each somite further differentiates regionally; a process called metamerism and ultimately differentiate either into myotomes to become spinal musculature, or into dermatomes to form skin.

An infolding of mesoderm is thought to be formed by the presence of regionally specific cell signaling factors, creating the neural groove. The neural tube will ultimately form from this groove, which is the precursor to the spinal cord. The peripheral nervous system will begin to develop from neural crest cells during neurulation.³

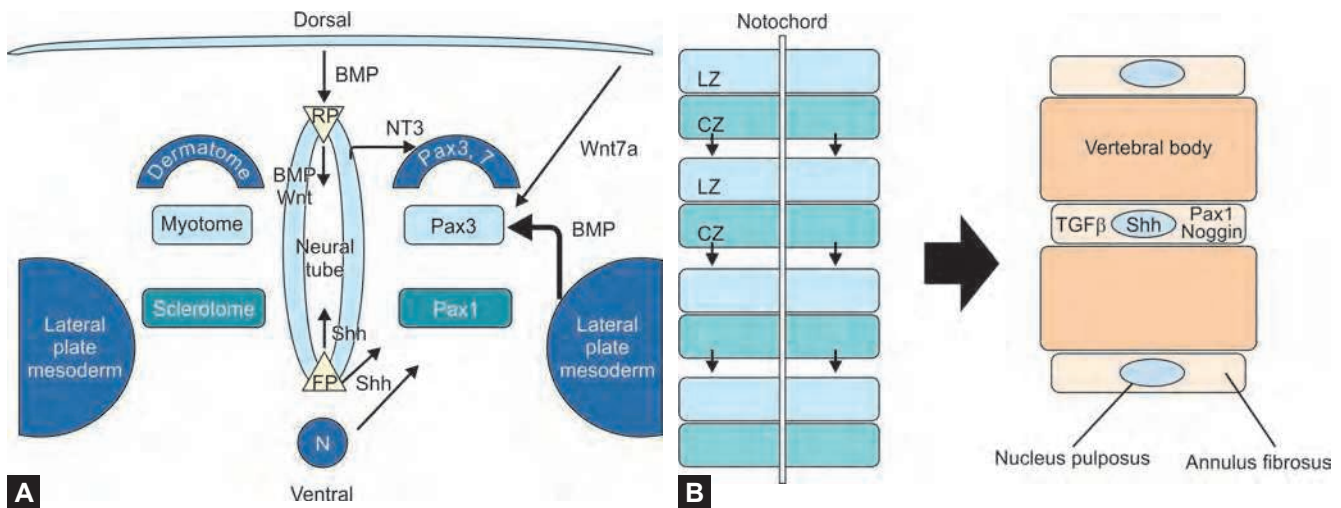
Precartilaginous Stage

At approximately week 4, the mesenchymal cells will divide into three regions: surrounding the notochord, neural tube, and within the body wall. Also at this time, paraxial mesoderm begins to form the precursor of the vertebral column, of bone and disk, the dermis, striated muscle, and connective tissue.⁴

Cartilaginous Stage

At approximately week 6, after cell migration and vertebral body fusion begins, chondrification centers begin to develop within each vertebrae.² Two of these centers in the centrum will fuse to form a large segment of cartilage. Ultimately, sclerotomal proliferation and then differentiation will surround this cartilage to form the annulus fibrosis. Central disintegration of the cartilaginous centrum will then contribute to the nucleus pulposus.² The annulus of the disc starts off as dense cellular regions surrounding the notochord alternating with vertebral bodies.

Segmentation is known as the division of the paraxial presomitic mesoderm (PSM) into somites. These somites are arranged symmetrically in pairs alongside the neural tube and will later form the sclerotome, dermatome, and myotome. Segmentation occurs shortly after gastrulation (20–35 days after conception). Each somite block is affected by different signals in the dorsoventral axis of the



Figs. 17.1A and B: (A) Division of the paraxial presomitic mesoderm (PSM) into somites, (B) the formation of the vertebral body.

embryo. Dorsal somites differentiate into dermatomes by NT-3 signaling from the neural tube, middle somites into myotomes by Wnt7a signaling, and ventral somites differentiate into sclerotomes by Sonic Hedgehog Gene (SHH) signaling from the notochord and floor plate (Fig. 17.1A).⁵

This process continues until a preprogrammed number of somite blocks are formed (33 blocks in humans).⁶ The genetics and pathological disorders resulting from aberrant segmentation will be discussed next.

Molecular Mechanism in the Development of Spine

Cells of the sclerotome, expressing Pax1 and Pax9, begin to migrate toward and around the notochord and neural tube. Once the sclerotomes have surrounded the notochord and neural tube, each level will separate into a cranial area of loosely packed cells (loosed zone; LZ) and a caudal area of densely packed cells (condensed zone; CZ) (Fig. 17.1B). The intervertebral disc will form between these two layers of cells. Some cells in the CZ migrate cranially and differentiate into the annulus fibrosis by expressing transforming growth factor beta, Pax1, and Noggin. The remaining cells in the CZ fuse with the adjacent cells in the caudal LZ and form centrum that expresses Sox9 and Col II. This centrum develops further into the vertebral body by expressing bone morphogenetic protein (BMP). Thus, one complete vertebra consists of two somites to interact properly with each other in order to develop normally. The nucleus pulposus will develop inside the annulus from notochord that does not deteriorate.⁷

The patterned formation of cartilage into annulus and nucleus is dependent on gene expression, seen in chondrogenic tissues relative to nonchondrogenic tissues. This is accomplished by alternative splicing of mRNA, producing procollagen II and collagen IX. Sclerotomal cells differentiate into chondrocytes in vertebral bodies when they start producing short type IX collagen. Cells destined to become cartilage express procollagen alpha II, and cells destined to become bone have a longer structural form of type II procollagen that results in the characteristic hardness and structural relationships of vertebral body and disk.

Ossification Stage

Two primary ossification centers are found at each spinal level, one in the centrum of the future vertebral body and other in the vertebral arch. This typically begins in the midthoracic spine and then progresses in a cranial-caudal direction.⁸ Each vertebra is formed from an adjacent cranial and caudal sclerotome. The fusion of these two constitutes a centrum, the embryological precursor to the vertebral body.⁹ Recent discoveries in the hox and pax genes have elucidated their contributions in this matter. Five secondary ossification centers form after birth: transverse processes bilaterally, the tip of the spinous process, and the cranial and caudal surface of the vertebral body.

GENETIC INFLUENCE ON SPINAL DEVELOPMENT

Modern advances in laboratory techniques have expanded our understanding of genetic expression and spinal

development, in addition to positional-dependent induction of neurulation. Wnt and/or fibroblast growth factor (FGF) signaling pathways and BMP activity have been implicated in the organization and induction of gastrulation.¹⁰

Lateral/paraxial mesoderm has been recently thought to be the source of endogenous posteriorizing factors (factors that are key in ensuring a dorsal site of neural induction). Wnt plays a key role in posteriorizing the neuroectoderm. Currently, it is still unclear whether overt posteriorization occurs *in vivo* or which endogenous ligand exerts the transforming influence from lateral mesodermal cells.

Wnt8, another signaling molecule, seems to be correlated with neural anteroposterior patterning, where inactivation of Wnt8 function inhibits formation of spinal cord, hindbrain, and the midbrain–hindbrain boundary without disrupting ventrolateral mesoderm formation.

Modern understanding of spinal cord development at a cellular level has also grown considerably.^{10–13} The development of the spinal cord is dependent on the polarized pattern of expression of regulatory genes and a variety of growth factors.¹¹ The notochord has a role in dorsoventral patterning of the neural tube, without the notochord, the floor plate does not form and motoneurons fail to develop. However, when the neural tube is closed, floor plate and motoneurons develop normally without notochord. Hence, polarization of spinal cord takes place during a well-defined temporal window.¹⁰

Dorsoventral Differentiation of the Neuroaxis

The differentiation of neurons along a dorsoventral axis is of vital importance to organization and development of the spinal cord. Dorsoventral polarization of the spine occurs through a combination of dorsalizing and ventralizing signals from dorsal and ventral midline.¹² Diffusion of molecules encoded by gene expression in the notochord and floor plate thus induce position-dependent growth. One vital signal is a product of the SHH that originates from the notochord and floor plate. This signal initially suppresses dorsalizing signals, hence causing more ventralization. When a ventral identity is formed, graded SHH signals cue development of specific neurons and glial cells. Ventral neurons are derived from the ventricular surface of the basal plate where neuroepithelial precursors are located.

These precursors generate postmitotic progenitor cells that will migrate radially and differentiate into motor and interneurons, both express LIM-homeodomain transcription factors. Depending on the local concentration of SHH along the dorsal–ventral axis, the precursors of different type of neurons can be found. Signals from paraxial and surface mesoderm influence regional specificity of motor neuron subtype along anterior–posterior axis. Intracellular effects of SHH signaling are mediated in part by Pax6 a transcription factor.¹¹ Sonic Hedgehog Gene represses Pax6, hence dorsal half of neural tube will have higher concentration of Pax6 establishing a concentration gradient. Pax6 in turn represses expression of transcription factor Nkx2.2. Pax6-positive areas generate somatic motor neurons of the median motor column that express LIM-domain proteins Isl1, Isl2, Lim3 aka Lhx3, and Gsh4 aka Lhx4.¹¹ Precursors from Pax6-negative generate ventral interneurons that express different combinations of Pax2, En1, Evx1, Lim1, Lim3, Gsh4, and Chx10. Nkx2.2-positive areas generate a subset of motoneurons expressing Isl1 but not Isl2 and a population of cells that express Sim1. Glial cells are also derived from precursors in the ventral half of spinal cord. Development of oligodendrocyte progenitor cells depends on SHH signaling. Oligodendrocyte progenitor cells arise from the ventral-most region of Pax6-positive domain at the ventricular zone of spinal cord, the same area that is thought to give rise to somatic motor neurons of the median motor complex.

DEVELOPMENT OF THE VERTEBRAL COLUMN

Development of the vertebral column takes years, as complete ossification of the halves of the vertebral arch by cells migrating adjacent the neural tube will complete approximately at 6 years of life.¹ Somites in a particular sclerotome, the precursor to the vertebral column, divides into a rostral and caudal portion, whereby migration and differentiation are due to signals expressed by the pax and HOX genes.² The cranial aspect of one sclerotome will fuse to the caudal aspect of an adjacent sclerotome, forming a vertebral body.

DEVELOPMENT OF THE SPINAL CORD

In the third week, invagination of the ectoderm differentiates into mesoderm cells, which ultimately differentiates into the notochord. The migration of these cells was recently understood, through modern scientific advances

in cell signaling.¹⁴ Failure of closure of the neural tube results in a common congenital defect, termed spina bifida. The spectrum of presentations of this disease will be discussed next, ranging from an occult defect in the posterior elements (spina bifida occulta) to a herniation of the neural elements and thecal sac through a laminar defect typically presenting in severe neurological deficits.

Week 5 marks the formation of the alar and basal plate, which are proliferations of tissue on the dorsal and ventral neural tube, respectively. The separation between these two plates is the sulcus limitans, which will eventually separate the sensory from the motor tracts. This division will involute by week 6, followed by the formation of white matter tracts by weeks 7 and 8.

■ POSTNATAL MATURATION OF THE SPINE

The spinal canal has obtained its maximum diameter usually by 8 years of age. While ossification centers, as mentioned above, contribute to maturation of the spine, it is the presence of thin chondroepiphyseal regions on the end plates that contributes to the circumferential growth. This growth is evident on imaging as growth plates, which must be distinguished from fracture. Ossification centers may continue to proliferate and differentiate up to 25-year-olds. Neonatal spinal conformation has a predominating kyphosis of the thoracic spine. Secondary curvatures will then develop as the child becomes ambulatory.

Molecular Marker of the Developmental Spine and Spinal Cord

Recent studies show that there are some specific or selective molecular markers of spine and spinal cord tissues in each developmental stage. It is important to be familiar with these markers to have a better understanding of both normal and abnormal development of the spine and spinal cord. Actually, many researchers label these markers of interests with lacZ or enhanced green fluorescent protein *in vivo*, or develop conditional gene expression model using Cre-loxP system and analyze the phenotype.¹⁵⁻¹⁷

■ CONGENITAL MALFORMATIONS OF THE SPINE

Modern advances in genetic techniques have shed light on the pathogenesis of some particularly devastating diseases.

The presence of one congenital spinal deformity should prompt a further diagnostic inquiry, as studies indicate an incidence of 30% to as high as 60% for additional abnormalities.¹⁸ Through the understanding of the pathogenesis, we have gained a more clear understanding of the normal mechanism of development. Classification of congenital malformations of the spine consists of defects of the neural tube, defects of formation and defects of segmentation.

Neural Tube Defects

The period of gestation between 3 and 4 weeks is when neurulation occurs. Disorders in neurulation have an incidence as high as 1 in 1000 live births in the United States.^{19,20} Preindustrial nations lacking adequate folate carry an even higher incidence. Since 1991, the CDC recommends 4 mg of folate per day for pregnant women, and this is credited as the declining incidence in the industrialized world. Mutations in the methylene tetrahydrofolate reductase gene causing a decrease in its activity is thought to be a risk factor for spina bifida in both mother and child.²¹ Other theories point to elevated homocysteine levels, a consequence of low folic acid intake.²²

Spinal dysraphism refers to failure of fusion of posterior midline structures of the spine. Spina bifida is a condition where the posterior, bony arches fail to fuse.^{19,23} This condition is associated with the TIVS7-2 axial mesoderm allele and spina bifida.²¹ Multiple alleles have been discovered in the past 20 years, whose mutation has a predilection for spina bifida.²⁴⁻²⁶

Further classification of spinal dysraphism is delineated by the presence or absence of intact, overlying skin: spina bifida occulta and spina bifida cystica. The incidence of spina bifida occulta occurs in 24% of the normal population, in select studies.^{27,1} Spina bifida cystica includes myelomeningocele, involving herniation of elements through the bony defect and skin, whereas spina bifida occulta is denoted by the presence of cutaneous irregularity or other stigmata, which serve as clues for underlying disease. Various additional neurological conditions may be present in the diagnosis of spina bifida including Chiari malformation, hydromyelia, and tethered cord.

Myelomeningocele are typically closed within 72 hours of delivery to prevent infections, neurological worsening, or death.²⁸ More recent retrospective data suggests that closure on first day of life may have the best chance for reducing the incidence of a neurogenic bladder.²⁹ The goal of the procedure is to re-establish tissue planes (pia-arachnoid, dura, fascia, skin) and obtain a watertight

closure to allow for maximum barrier between the nervous system and surface bacteria. As high as 85% of the time, hydrocephalus is present, and ventriculoperitoneal shunting may be required for wound healing as well as neurologic development.

One alternative to perinatal myelomeningocele closure is intrauterine surgery during gestation. In a recent randomized trial of prenatal versus postnatal repair of myelomeningocele, fewer infants reached a composite primary outcome of death or need for ventriculoperitoneal shunt at 12 months (68% versus 98% need for shunting).³⁰ The overall rate of ventriculoperitoneal shunt placement was less in the prenatal surgery group with superior mental development and motor function at 30 months.

An additional form of spinal dysraphism is a lipomyelomeningocele, which arises from a failure of disjunction between ectoderm and neuroectoderm. The residual fat attaches dorsally on the conus and protrudes through the defect in the posterior elements. Caudal attachments appear as a continuation of the spinal cord, with a lipomatous mass, and an uncommon transitional form is of note, which can make surgical planning difficult.³¹⁻³³

Failure of Development

VATER is a term coined by Quan and Smith in 1972 to describe the clinical presentation of two or more of the following congenital abnormalities: vertebral defects, anal atresia, tracheoesophageal fistula, and radial limb defects.³⁴ Renal defects were added a year later to the list, and while vertebral defects are seen the most often, many other congenital defects are seen in conjunction with the VATER, but with a decreased frequency.

Among the most common abnormalities seen with VATER are Klippel-Feil syndrome, a congenital fusion of one or more of the cervical vertebrae, and Sprengel deformity, a failure of descent of the scapula, leading to an asymmetrically elevated scapula.

The most commonly involved organ system dysfunction in the presence of a diagnosed congenital spinal deformity is the genitourinary system; with an incidence of as high as 20%.³⁵ Other diagnostic clues include a single umbilical artery, which has a higher incidence of congenital malformation and association with VATER/VACTERL.³⁶

The VACTERL/VATER association further recognizes the underlying genetic contribution to the pathogenesis of this disease. VACTERL stands for vertebral defects, anal atresia, cardiac defects, tracheoesophageal fistula, renal

anomalies, and limb defects. A diagnosis requires three or more findings and is seen as often as 1 in 10,000 live births.³⁶

The developmental field defect may explain the constellation of findings in which developmental malformations in blastogenesis would affect multiple organ systems. As of yet, there are no single genetic underlying defect to explain these disease entities and as a result are not syndromal.³⁶

The closest to a disease pathway have been shown in animal models where mutations in SHH pathway genes SHH and Gli have led to VACTERL-like phenotypes. In humans, SHH loss of function mutations commonly lead to holoprosencephaly, not seen commonly with VACTERL.³⁶⁻³⁸ Similarly, mutations in HOXD13 and FOXP1, both linked to SHH signaling, have been associated with VACTERL-like defects. Many other syndromes, with known gene mutations, such as Fanconi anemia, Feingold syndrome, Holt-Oram syndrome, and CHARGE^{39,40} syndrome, have similar presentations to VACTERL.⁴¹⁻⁴³

FAILURE OF SPINE DEVELOPMENT

Failure of Formation

Failures of formation are defined as the absence of any structural component of the vertebral body, resulting in a spinal deformity.¹ Hemivertebrae and wedge vertebrae, are common defects that have been observed to contribute to pediatric spinal deformities as well as adults. Hemivertebrae is primarily a failure of formation, but may overlap with defects of segmentation. They can be fully segmented, semisegmented, and nonsegmented.¹ In the case of a semisegmented vertebrae, there is a functional growth plate on one side only. In the nonsegmented vertebrae, there is an absence of a growth plate and the least contribution to deformity.

Failure of Segmentation

Segmentation is known as the division of the paraxial PSM into somites. These somites are arranged symmetrically in pairs alongside the neural tube and will later form sclerotome, dermatome, and myotome. Segmentation occurs shortly after gastrulation (20-35 days after conception). This process continues until a preprogrammed number of somite blocks are formed (33 blocks in humans).⁶ Somitogenesis is a regulated process that begins at the caudal area followed by the rostral area. This process consists of

two signaling processes: the clock and the wavefront. The clock is made up of genes whose expression oscillates with the amount of time it takes for a somite to form (4–6 hours).^{6,44} The wavefront is formed by a signaling gradient from FGF8 in the caudal PSM, which opposes another gradient from retinoic acid in the rostral PSM.⁶

The clock is regulated by the cyclical induction of Notch1 receptor, signaling crucial genes in the PSM cells: delta-like 3 (DLL3), Mesoderm Posterior 2 (MESP2), and Lunatic fringe (LFNG).^{44,45} Besides, Notch signaling is required for somite boundary formation and somites' anterior–posterior identity. DLL3 refines Notch1 signaling by inducing lysosomal degradation of Notch1 proteins. Without it, somite formation and patterning are irregular causing type I spondylocostal dysostosis (SCD).^{44,45} Spondylocostal dysostosis is classified into three types, SCD1, SCD2, and SCD3. They are characterized by rib fusions, rib deletions, hemivertebrae and loss of vertebrae leading to truncal shortening. Spondylocostal dysostosis 2 is classified by the involvement of the thoracic vertebrae with only mild deformity in the lumbar vertebrae. Mesoderm posterior 2 is crucial in somitogenesis of the rostral PSM and in defining the rostrocaudal polarity of the sclerotome. A mutation in that gene would cause SCD 2.⁴⁵ Spondylocostal dysostosis 3 is caused by mutated LFNG. This is characterized by abnormalities in somite formation and anterior–posterior somite identity resulting in severe axial skeletal defects and reduced numbers of caudal vertebrae.⁴⁵ However, only 30% of SCD cases are caused by mutations of these genes,⁴⁶ where DLL3 is the most commonly affected gene.⁴⁵

Failures of segmentation involve two or more adjacent vertebrae. These vertebrae fail to divide, resulting in a partial or complete loss of the growth plate.¹ A block vertebrae forms when an entire vertebrae is involved. Unilateral bar vertebrae occur as an asymmetric rigid fusion of multiple vertebrae, causing asymmetric growth. Failure of segmentation and formation failures surely overlap, as the underlying processes are similar.

Failure of Spine Maturation and Scoliosis

Abnormal spinal curvature as a result of failures of formation and segmentation are the hallmarks of congenital scoliosis (CS). Most commonly, the primary curvature is seen to involve the thoracic spine 64% of the time.⁴⁷ The vast majority of these curves are progressive, giving the poorest prognosis to curves greater than 50° by age of 2 years.⁴⁸ Prior to any surgical decision, diagnostic workup

will demonstrate various associated congenital problems (e.g. VACTERL/VACTER).

Spondylothoracic dysostosis (STD) is another abnormal vertebral malformation disease initially described by Jarcho and Levin.⁴⁹ It differs from SCD by its variability in rib length and alignment and points of intercostal fusion.⁴⁵ Alternatively, STD is classified as the fusion of all ribs at the costovertebral junctions resulting in a crab-like appearance with defective vertebral segmentation and formation defects along the spine.⁵⁰ Spondylothoracic dysostosis is also associated with other anomalies such as imperforate anus, genitourinary abnormalities, diaphragmatic hernia, choanal stenosis, and cleft palate.⁶ Interestingly, STD has a high prevalence rate in people from Puerto Rico, which is thought to be due to a recessive mutation in MESP2 and E103X.⁴⁵

There are two syndromes associated with defective segmentation; Alagille syndrome (AGS) and Klippel–Feil syndrome. Alagille syndrome is an autosomal dominant disease characterized by facial dysmorphism, scarce bile ducts, defective heart, eye, kidney, pancreas, and skeleton.⁵¹ A butterfly vertebra is seen in 22–87% of people affected by AGS.⁴⁵ Mutations of JAG165 are seen in about 70% of patients with this disease. However, haploinsufficiency of JAGGED1 gene has been proposed to be the main mechanism of AGS.⁶ Those with severe renal manifestation have mutations in NOTCH2.⁵²

Klippel–Feil syndrome is a condition with abnormalities of the cervical spine due to faulty segmentation.⁵³ It can be an autosomal dominant, autosomal recessive, or an X-linked condition. This disease is classified into three types, type I in those with severe fusions of many cervical vertebrae, type II in those with only one or two cervical interspaces fused and type III in those with additional fusions in the lower lumbar spine.⁵⁴ First described in 1894,⁵³ it is associated with diverse organ system malformations, namely neural tube defects, thoracic cage abnormalities, pulmonary, cardiovascular and other skeletal anomalies, genitourinary abnormalities, myopathy, neuropathy, and cognitive disorders.⁵⁵ PAX1 and HOX mutations may have a role in developing this disease.⁵⁵ Another gene known as GDF6, which is part of the WW BMP family, is associated with joint and vertebral formation (Table 17.1). Abnormalities in this gene may contribute to the joint fusions in Klippel–Feil syndrome.⁵⁶

Nonsyndromic vertebral malformations due to defective segmentation include CS and idiopathic scoliosis (IS). Congenital scoliosis can be caused by defective formation

Table 17.1: Selected tissues and known associated developmental markers.

<i>Tissues</i>	<i>Molecular markers</i>
Roof plate	BMP, Wnt1, Wnt3a
Notochord	SHH, Foxa2, T
Floor plate	SHH, Foxa2
Somite	Paraxis
Sclerotome	Pax1
Neural tube	Pax3, Pax6, Pax7
Neural crest	P0, Wnt

of vertebrae and defective segmentations. Anomalies of segmentations are unilateral failure of segmentation and bilateral failure of segmentation. Abnormalities of formation would include unilateral complete failure of formation of vertebra resulting in hemivertebra, nonsegmentation, incarceration of vertebra, and unilateral partial failure of formation causing wedge vertebra.⁴⁵ Congenital scoliosis is associated with many abnormalities such as esophageal atresia, tracheoesophageal fistula, diastematomyelia, anal atresia, Sprengel deformity, facial asymmetry and bladder, and cloacal exstrophy.⁵⁷⁻⁵⁹ Genitourinary abnormalities are particularly more frequent (43%) in patients with CS as they both arise from the mesoderm during the fifth week of embryogenesis.⁴⁵ Renal defects are found in 13% of CS patients.⁶⁰ Other causes of the defect include failures of spinal growth, teratogenic agents, and intrinsic genetic abnormalities.¹⁸ Some evidence suggests that organ malformations correspond to the level of the affected vertebrae.⁶¹ Most of the time congenital scoliosis, if left untreated, will result in progression of the disease, leading to a worse prognosis. One condition like this is CS, which is caused by a unilateral failure of vertebral segmentation with contralateral hemivertebrae. During growth of the child, the hemivertebrae that contain epiphyseal plates grow longitudinally, whereas the unilateral unsegmented bar do not grow because of absent epiphyseal plates. This leads to a crankshaft effect, which causes a rapidly progressive scoliosis. The tethering effect of the unsegmented bar on the concavity of the spine growth further aggravates the situation.⁴⁸

Surgery during the first year of life is recommended to manage this disease. Fusion of the spine by combined anterior and posterior arthrodesis has been proven to overcome the crankshaft effect. Caution must be taken to monitor a secondary curve that will result from the

primary CS. The secondary curve will still develop regardless of the fusion of the primary curve. Hence, prophylactic bracing of the secondary curve can be done.⁴⁸

Idiopathic scoliosis is a diagnosis of exclusion with no definite etiology. It is classified into infantile, juvenile, and adolescent scoliosis.⁶² However, a recent research involving 237 families with at least one CS case in each family shows that 17.3% of the sample reported having members with IS.⁶³ This suggests that IS and CS may have a genetic correlation. A gene that was postulated is the CHD7 gene that is associated with the CHARGE syndrome. Seventy percent of CHARGE patients have late-onset IS.⁶⁴

Like all other congenital abnormalities, teratogens have a role in vertebral malformations too. Substances such as alcohol⁶⁵⁻⁶⁷ (cervical fusion), valproic acid (neural tube defects),⁶⁷ and dilantin (not a strong teratogen)⁶⁸ have been associated with vertebral malformations. Uncontrolled maternal diabetes is also implicated in vertebral malformations. It leads to regression of the caudal spine and agenesis of the lower vertebral column.⁶⁹ Some mechanisms of actions include teratogen-induced embryonic cardiac arrhythmia, which causes transient hypoxia and reoxygenation injury, carbon monoxide poisoning causing altered expression of sonic Hedgehog gene and boric acid altering HOX gene expression pattern.⁴⁵

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Anatomy and Physiology of Congenital Spinal Lesions

Mamoru Kawakami

Snapshot

- » Embryology of the Spine and Spinal Cord
- » Congenital Anomalies of the Cervical Spine
- » Basilar Impression and Basilar Invagination
- » Occipitalization of the Atlas
- » Arnold-Chiari Malformation
- » Congenital Anomalies of the Atlantoaxial Joint
- » Congenital Anomalies of the Odontoid
- » Klippel-Feil Syndrome
- » Congenital Stenosis of the Cervical Spinal Canal
- » Spinal Dysraphisms
- » Spinal Meningeal Cyst
- » Congenital Spinal Deformities
- » Failure of Formation
- » Failure of Segmentation
- » Congenital Scoliosis
- » Congenital Kyphosis
- » Congenital Lordosis
- » Congenital Spondylolisthesis
- » Congenital Spinal Stenosis

INTRODUCTION

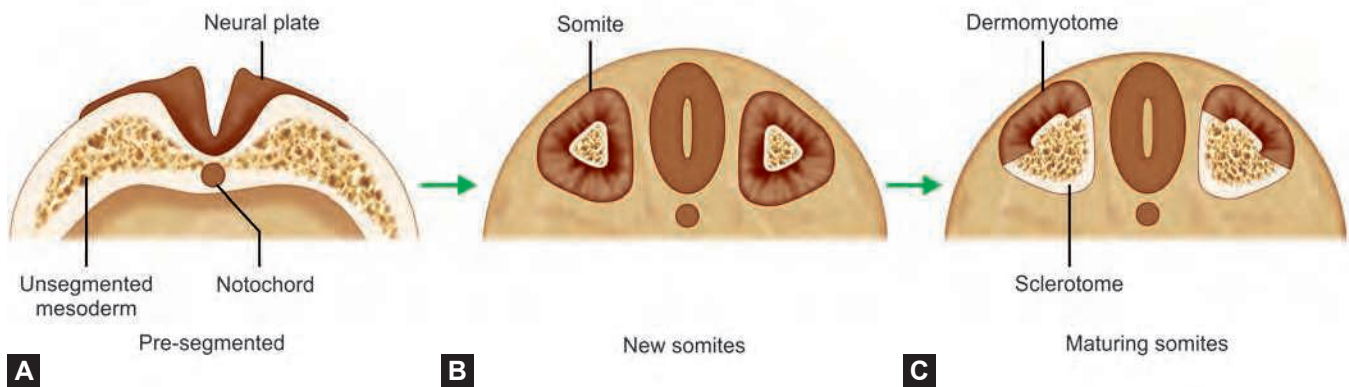
Congenital spinal lesions are involved in congenital malformations of the spine and spinal cord such as spinal dysraphisms and congenital spinal deformities, which are caused by congenitally anomalous vertebral development. The evaluation of these disorders requires an understanding of anatomic and developmental features of the spine. In this chapter, the developmental anatomy of the spine is briefly reviewed. The anatomy and physiology of these congenital spinal lesions are described individually.

EMBRYOLOGY OF THE SPINE AND SPINAL CORD¹⁻³

During the third weeks of gestation, a definitive notochord forms between the ectoderm and endoderm. At the cephalic end of the embryo, the ectoderm immediately above the notochord begins to thicken and differentiate into neuroectoderm, which forms the neural plate. The neural plate then begins to buckle along its midline to

shape the neural groove, walled in by a neural fold on the either side. While this process occurs, a loose collection of intraembryonic mesenchymal cells begins to coalesce into three regions. The most medial becomes a solid mass, the paraxial mesoderm, which is just lateral to the notochord and on its either side. The paraxial mesoderm is an anlage of the skeletal muscle, bone, and skin. By the end of the third week, this mesoderm begins to segment in a cranial to caudal direction. In the somite stage, corresponding to the 30 days of gestation, a total 42–44 somites appear. There are 4 occipital, 8 cervical, 12 thoracic, 5 lumbar, 5 sacral, and 8–10 coccygeal pairs. Each somite differentiates into three parts, of which the ventromedial cell mass differentiates to form the sclerotomes, destined to form the vertebral bodies. These bilateral ventromedial cells migrate to the mid line and surround the notochord. Each somite separates into a caudal and a cephalic portion, with the cells of the middle portion condensing to form the intervertebral disc (Figs. 18.1A to C).⁴

In the occipitocervical spines, the four sclerotomes corresponding to the three primary roots of the hypoglossal



Figs. 18.1A to C: Somitogenesis in the embryo. Cross-sections of the developing embryo are shown, representing the different stages of patterning in somitogenesis, which takes place between 20 and 30 days of gestation. (A) Prior to formation of the somite segments, the neural plate is folding to eventually form the neural tube, which is the precursor to the adult spinal cord. The tissue that will form somites is unsegmented, and lies to the side of the notochord, which contributes to the intervertebral disks in the adult. (B) Upon segmentation, the somites are formed as a pair of spherical ball of cells on the either side of the future spinal cord. (C) As the somites mature, the sections nearest the gut migrate away to form the sclerotome, the precursors to the vertebral bones. The remaining dermomyotome forms the muscles of the spine, and the dermis in the skin.⁴

nerve fuse to form the occipital bone. The fourth sclerotome of this complex divides into an anterior and a posterior segment. Subsequently, the anterior segment of the most caudal part of the occipital sclerotome and the most cranial segment of the first cervical sclerotome fuse to form the atlas. The anterior portion of the first and second cervical sclerotomes fuses to form the axis. Any congenital deformity in this region is formed not later than this embryological age. Ossification of these bones appears around the eighth week and is completed in the third year of life except for the odontoid tip, which may not ossify until the age of 12.

Simultaneous with development of the cartilaginous skeleton, differentiation of the nervous system progresses. The neural plate begins to take on a tube-like appearance by the end of the third week. During the fourth week, the neural folds that form the sidewalls start to fuse in the middle line to form a true tube. Fusion of the neural tube proceeds simultaneously in a cephalad and caudad direction, closing along its entire length by the end of the fourth week. The size of the neural tube determines the diameter of the developing spinal canal. During the fifth and sixth week, further differentiation of the various parts of the brain and spinal cord occurs.

CONGENITAL ANOMALIES OF THE CERVICAL SPINE

Congenital anomalies have a varied spectrum ranging from benign asymptomatic conditions to those with a

potential for fatal instability. Congenital causes of cervical spine instability are complex because congenital vertebral anomalies of the cervical spine arise from defective somatogenesis. Congenital anomalies of the cervical spine often occur in clusters, which further complicates these cases because more than one congenital anomaly frequently exists in the same patient. Many developmental anomalies of the craniovertebral junction have been described in the literature in a rather confusing fashion and usually as separate entities. However, each anomaly is usually accompanied by others. Any developmental anomaly of this region can be ectodermal, mesodermal, or a combination of these two germ layers. A classification of these anomalies, depending on embryological development, is simple and facilitates understanding of this complex problem² (Table 18.1). The “minor anomaly” consists of a developmental anomaly or anomalies of a single-germ layer, which can be mesodermal or ectodermal. The term “major anomaly” covers a combination of different germ layers.

BASILAR IMPRESSION AND BASILAR INVAGINATION

Basilar impression is defined as upward displacement of the dens into the normal foramen magnum with normal bone, while basilar invagination is a similar displacement due to softening of bones at the base of the skull. Thus, different terms are used according to whether bone is normal or not. With this anomaly, the dens are displaced

Table 18.1: Classification of craniovertebral anomalies.

Minor mesodermal asymptomatic anomalies	Arch anomalies of atlas Arch anomalies of axis Atlanto-occipital articulation anomalies Occipital condyle asymmetries Occipital vertebrae
Minor ectodermal asymptomatic anomalies	Blind dermal sinus Intradural fibrous bands
Minor mesodermal symptomatic anomalies	Occipitalization of atlas Hypoplastic atlas Odontoid hypoplasia Odontoid agenesis Os odontoideum Congenital atlantoaxial instability Basilar impression
Minor ectodermal symptomatic anomalies	Syringomyelia of neighboring cord Arnold-Chiari type I malformation
Major anomalies	Arnold-Chiari type II-III malformation with spinal dysraphism Syringomyelia with basilar impression

cranially through the foramen magnum to encroach the brainstem. It is commonly associated with other anomalies such as Klippel-Feil syndrome (KFS), hypoplastic atlas, and occipitocervical synostosis. It may also accompany systematic disorders such as achondroplasia, osteogenesis imperfecta, and Morquio-Brailsford syndrome.

A plain lateral X-ray, with odontoid views, is a good place to start (Fig. 18.2). Chamberlain's line is drawn between the posterior hard palate and the posterior edge of the foramen magnum. The normal position of the dens is between 1 mm below this line and as much as 0.6 mm above it. McGregor's line is the line drawn from the posterior hard palate to the base of the occiput. Protrusion of the tip of the dens greater than 4.5 mm above this line is abnormal. McRae's line extends from the basion to the posterior lip of the foramen magnum. Protrusion of the tip of the dens above McRae's line is indicative of basilar invagination. A plain computed tomography (CT) scan with sagittal reconstructions can also document this, but magnetic resonance imaging (MRI) provides more information.

■ OCCIPITALIZATION OF THE ATLAS

Occipitalization is a congenital synostosis of the atlas to the occiput, which is a result of failure of segmentation and separation of the most caudal occipital sclerotome

and the first cervical sclerotome during the first few weeks of fetal life.³ There may be varying degrees of bony fusion between atlas and occiput. In a majority of cases, assimilation occurs between the anterior arch of the atlas and the anterior rim of the foramen magnum and is associated with other skeletal malformations such as basilar invagination, occipital vertebra, spina bifida of atlas, or fusion of the C2-3 vertebrae (KFS).

■ ARNOLD-CHIARI MALFORMATION

Arnold-Chiari malformation is a malformation of the brain. It consists of a downward displacement of the cerebellar tonsils through the foramen magnum, sometimes causing noncommunicating hydrocephalus as a result of obstruction of cerebrospinal fluid outflow. Arnold-Chiari malformation is classified into types I, II, III, and IV (Table 18.2).

The most widely accepted pathophysiological mechanism by which Arnold-Chiari type I malformations occur is by a reduction or lack of development of the posterior fossa as a result of either congenital or acquired disorders. Congenital causes include hydrocephalus, craniosynostosis (especially of the lambdoid suture), hyperostosis (e.g. craniometaphyseal dysplasia, osteopetrosis, erythroid hyperplasia), X-linked vitamin D-rickets, and neurofibromatosis type I.

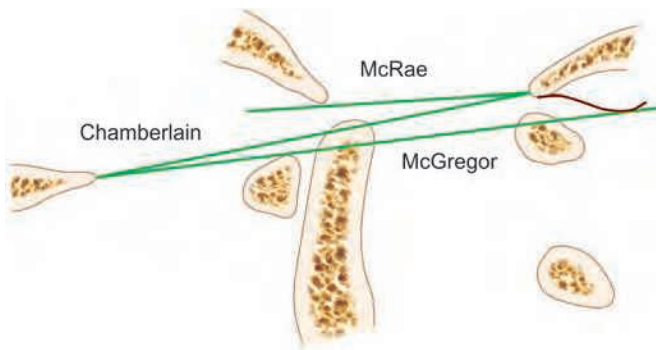
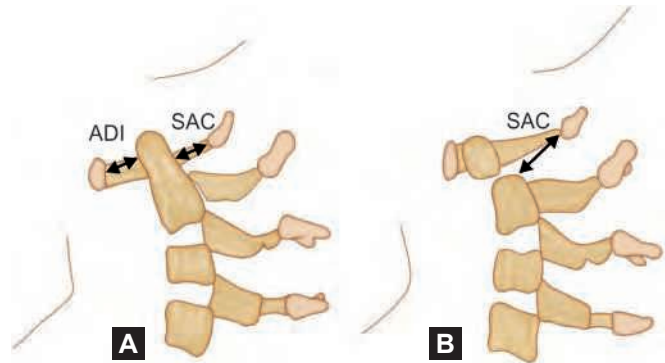


Fig. 18.2: McRae line is a radiographic line drawn on a lateral radiograph of skull, joining the anterior (basion) and posterior (opisthion) aspects of foramen magnum. Normal position of the tip of dens is 5 mm below this line. If the tip of the dens migrates above this line it indicates the presence of basilar invagination. Chamberlain's line is drawn between the posterior hard palate to the posterior edge of the foramen magnum. If the dens is more than 3 mm above this line, the patient has basilar invagination. The McGregor line is a modification of the Chamberlain line and is used in the evaluation of basilar invagination when the opisthion could not be identified on plain radiographs. It refers to a line connecting posterior edge of the hard palate to the most caudal point of the occipital curve. If the tip of the dens lies more than 4.5 mm above this line it is indicative of basilar invagination.

Table 18.2: Classification of Arnold-Chiari malformation.

Type	Presentation
I	<ul style="list-style-type: none"> • A congenital malformation • Herniation of cerebellar tonsils • Tonsillar ectopia of more than 3 mm below the foramen magnum • Syringomyelia of cervical or cervicothoracic spinal cord can be seen • Sometimes the medullary kink and brainstem elongation can be seen
II	<ul style="list-style-type: none"> • Usually accompanied by a lumbar myelomeningocele or lumbosacral spine with tonsillar herniation below the foramen magnum • As opposed to the less pronounced tonsillar herniation seen with Arnold-Chiari I, there is a larger cerebellar vermian displacement • Low-lying torcular herophili, which is important for distinction from Dandy-Walker syndrome, tectal beaking and hydrocephalus with consequent clival hypoplasia are classic anatomic associations • Colpocephaly may be seen due to the associated neural tube defect
III	<ul style="list-style-type: none"> • Associated with an occipital encephalocele containing a variety of abnormal neuroectodermal tissues • Syringomyelia and tethered cord as well as hydrocephalus are also seen
IV	<ul style="list-style-type: none"> • Characterized by a lack of cerebellar development in which the cerebellum and brainstem lie within the posterior fossa with no relation to the foramen magnum. Associated with hypoplasia



Figs. 18.3A and B: Atlantoaxial instability. (A) Intact odontoid. Flexion. Forward sliding of the atlas with an increased atlas-dens interval (ADI) and decreased space available for the spinal cord (SAC). (B) Os odontoideum. Forward sliding of the atlas with reduction of the SAC, but no change in ADI.

CONGENITAL ANOMALIES OF THE ATLANTOAXIAL JOINT

The congenital disorders involving the atlanto-odontoid articulation include hypoplasia or absence of the odontoid, occipitalization of the atlas as well as incompetence or absence of the transverse axial ligament, but the end result is narrowing of the spinal canal and impingement of the neural elements. Motion of the atlantoaxial articulation is usually accentuated in patients with bony anomalies of the occipitocervical junction. If an associated synostosis of C2-3 with occipitalization of the atlas exists, the additional stress on the atlantoaxial articulation may eventually lead to significant instability.

Congenital laxity of the transverse atlantal ligament is a diagnosis of exclusion suggested by the clinical occurrence of atlantoaxial dislocation without a predisposing cause such as history of trauma or congenital anomaly. This is a usually common in patient with Down's syndrome.

Radiological appearance of congenital atlantoaxial instability is important. The atlas-dens interval (ADI) is the space seen on the lateral X-ray between the anterior aspect of the dens and the posterior aspect of the anterior ring of the atlas (Figs. 18.3A and B). In children, the ADI should be no greater than 4.0 mm, particularly in flexion where the greatest distance can be noted. The amount of space available for the spinal cord (SAC) should be evaluated for a patient with os odontoideum or absent odontoid (Fig. 18.2). This is accomplished by measuring the distance from the aspect of the odontoid or axis to the nearest posterior structure (foramen magnum or the posterior ring of the atlas).

CONGENITAL ANOMALIES OF THE ODONTOID

Anomalies of the odontoid include complete aplasia, hypoplasia, and os odontoideum. All three conditions can produce symptoms and serious neurologic sequelae as a result of atlantoaxial instability. In developmental anatomy of the odontoid,⁵ summit ossification center for odontoid appears at 3–6 years and fuses with the odontoid by 12 years and basilar synchondrosis fuses by age of 7 years, on average. Subdental synchondrosis scar may remain as a remnant of this fusion. Two separate centers of the odontoid appear by the fifth fetal month and fuse with each other by the seventh fetal month. Synchondrosis between odontoid and neural arch and synchondrosis between odontoid and body fuses at 3–6 years. In young patients with incompletely ossified odontoid, a diagnosis of hypoplasia may be made in error. Hypoplasia of odontoid may be seen in conjunction with dysmorphic conditions such as achondroplasia or spondyloepiphyseal dysplasia. Os odontoideum, the most common anomaly, is currently believed to be traumatic in origin. In os odontoideum, the odontoid is an oval or round separated from the axis vertebra by a transverse gap. In imaging studies, a space is present between the body of the axis and a bony ossicle. The free ossicle of os odontoideum usually is half the size of a normal odontoid and is oval or round with smooth, sclerotic borders. Watanabe et al.⁶ reported that sagittal plane rotation angles, which calculated the difference of the atlantoaxial angle between the flexion and extension position is calculated, were more than 20°; or the instability index, which obtained from the change of SAC from flexion to extension, was more than 40% correlated with neurological signs and symptoms in patients with os odontoideum. It is important to evaluate the instability in congenital anomalies of the odontoid.

KLIPPEL-FEIL SYNDROME

Klippel-Feil syndrome, the congenital synostosis of the cervical vertebrae or brevicollis anomaly, refers to segmentation defects or fusion of the cervical spine. Short neck, low posterior hairline, and limitation of the movement of the head or the neck are the commonly described clinical features. The typical disorder results from a failure of the normal segmentation of the somites during weeks 3–8 of gestation. Growth differentiation factor (*GDF*) 6 and *GDF*3 gene mutations that cause KFS likely lead to a reduction in functional protein. While the *GDF*6 and *GDF*3 proteins

are involved in bone growth, and the *GDF*6 protein plays a role in the formation of vertebrae, it is unclear how a shortage in these proteins leads to incomplete separation of the vertebrae, specifically the cervical vertebrae, in patients with KFS.⁷ Associated abnormalities may include scoliosis (seen in 60%), spina bifida, Sprengel deformity (seen in 33%), genitourinary abnormalities such as malformed kidneys (occurs in 33%), anomalies of the ribs, cleft palate, respiratory problems, and heart malformations. The disorder also may be associated with abnormalities of the head and face, skeleton, sex organs, muscles, brain and spinal cord, arms, legs, and fingers.

The Klippel-Feil classification⁸ characterizes three different types of KFS showing specific morphologic features: type I displays a massive fusion of many cervical and upper thoracic vertebra with synostosis; in type II, the fusion is at only one or two interspaces, with hemivertebrae, occipitalization of the atlas, and other abnormalities in the cervical spine; and type III shows cervical fusions associated with lower thoracic or lumbar fusion. Most of the skeletal anomalies are found in type II of KFS. Syndrome anomalies dominate in type I KFS. Type II KFS with isolated synostosis of the cervical spine has the lowest risk for scoliotic development, whereas types I and III show progression of the curve.⁹

Samartzis et al.¹⁰ reported that specific fused patterns of the cervical spine in patients with KFS were associated with cervical spine related clinically significant symptoms. Axial symptoms of neck/headache, neck pain, and neck stiffness are the predominant symptoms in symptomatic KFS patients and are largely noted in patients who present with a single fused cervical segment. KFS patients with multiple congenitally fused segments are associated with a higher incidence and risk of developing radiculopathy or myelopathy, which is noted later in adolescence.

CONGENITAL STENOSIS OF THE CERVICAL SPINAL CANAL

Congenital stenosis means that the space in their spinal canal from birth is smaller than in most people. In many instances, the term spinal stenosis is used for actual spinal cord compression on diagnostic studies relative to the dimension of the cord for that person at other “normal” segments. The anteroposterior (AP) diameter of the normal adult male cervical canal is about 17 mm. Absolute cervical stenosis is associated with an AP diameter of less than 10 mm, whereas diameters of 10–13 mm are relative stenosis.

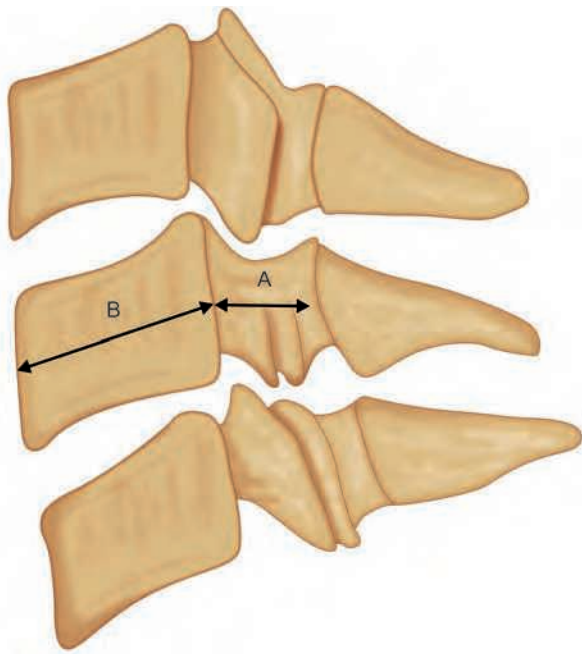


Fig. 18.4: The spinal canal to vertebral body ratio is the distance from the midpoint of the posterior aspect of the vertebral body to the nearest point on the corresponding spinolaminar line (A) divided by the anteroposterior width of the vertebral body (B).¹¹

Pavlov ratio (Ratio = AP diameter of cervical canal/width of cervical vertebral body) should be approximately 1.0 (Fig. 18.4). Less than 0.85 indicates stenosis, and less than 0.80 is a significant risk factor for myelopathy, radiculopathy, or both due to relatively minor spondylosis pathology or trauma neurologic injury in relatively minor trauma.¹¹ However, Blackley et al.¹² examined the reliability of this method using plain lateral radiographs of unknown magnification and CT scans and found that a poor correlation between the true diameter of the canal and the ratio of its sagittal diameter to that of the vertebral body. Therefore, CT scans or MRI is needed to evaluate the spinal canal of the cervical spine.

SPINAL DYSRAPHISMS

Congenital abnormalities of the spine and spinal cord are referred to as spinal dysraphisms. Spinal dysraphisms can be broadly categorized into open and closed types.¹³⁻¹⁵ In an open spinal dysraphism, there is a defect in the overlying skin, and the neural tissue is exposed to the environment. In a closed spinal dysraphism, the neural tissue is covered by skin. Closed spinal dysraphisms can be further subcategorized on the basis of the presence or absence of a subcutaneous mass.¹⁶

Congenital malformations are mostly due to the defective closure of the caudal neuropore at the end of week 4. The defects will involve the tissue overlying the spinal cord. Involving the spinal cord and vertebral arches are called spina bifida. Spina bifida occulta is a defect in the vertebral arch (neural arch) resulting from failure of the halves of the vertebral arch to grow normally and fuse in the median plane. Spina bifida cystica is a protrusion of the spinal cord and/or meninges through the defective neural arch. Spinal dermal sinus representing the area of closure of the caudal neuropore at the end of week 4 may exist. It is the last place of separation between the ectoderm and the neural tube. The dimple may be connected by a fibrous cord with the dura mater.

Simple dysraphic states consist of intradural lipoma, filar lipoma, tight filum terminale, persistent terminal ventricle, and dermal sinus. A dermal sinus is an epithelial lined fistula that connects neural tissue or meninges to the skin surface. It occurs most frequently in the lumbosacral region and is often associated with a spinal dermoid at the level of the cauda equina or conus medullaris.

Neurenteric cysts are found within the spinal canal and are lined by mucin-secreting, cuboidal or columnar epithelium resembling the gastrointestinal tract. Embryologically, neurenteric cysts may be due to endodermal differentiation of primitive-streak remnants, possibly related to incomplete regression of the neurenteric canal.

Diastatomyelia is characterized by a localized longitudinal separation of the spinal cord with an interposed septum. The two hemicords are usually symmetric, although the length of separation is variable. There are two types of diastatomyelia. In type I, the two hemicords are located within individual dural tubes separated by an osseous or cartilaginous septum. In type II, there is a single-dural tube containing two hemicords, sometimes with an intervening fibrous septum.¹⁷ Diastatomyelia can present clinically with scoliosis and tethered cord syndrome. Categorization of spinal dysraphisms is summarized in Table 18.3.¹⁸

SPINAL MENINGEAL CYST

The classification of spinal meningeal cysts in the literature is indistinct, confusing and in certain categories histologically misleading. Nabors et al.¹⁹ propose a classification comprising three categories: type I: extradural meningeal cyst without neural tissue. Type Ia: extradural spinal arachnoid cyst. Type Ib: sacral meningocele, type II:

Table 18.3: Summary of spinal dysraphisms.*1. Open spinal dysraphisms: not covered by intact skin*

Myelocele	Neural placode flush with skin surface
Myelomeningocele	Neural placode protrudes above skin surface
Hemimyocele	Myelocele associated with diastematomyelia
Hemimyelomeningocele	Myelomeningocele associated with diastematomyelia

*2. Closed spinal dysraphisms: covered by intact skin**(1) With a subcutaneous mass*

Lipomyelocele	Placode-lipoma interface within the spinal canal
Lipomyelomeningocele	Placode-lipoma interface outside of the spinal canal
Meningocele	Herniation of cerebrospinal fluid-filled sac lined by dura
Terminal myelocystocele	Terminal syrinx herniating into posterior meningocele
Myelocystocele	Dilated central canal herniating through posterior spina bifida

*(2) Without a subcutaneous mass**Simple dysraphic states*

Intradural lipoma	Lipoma within the dural sac
Filar lipoma	Fibrolipomatous thickening of filum
Tight filum terminale	Hypertrophy and shortening of filum
Persistent terminal ventricle	Persistent cavity within conus medullaris
Dermal sinus	Epithelial lined fistula between neural tissue and skin surface

(3) Complex dysraphic states

Dorsal enteric fistula	Connection between bowel and skin surface
Neurenteric cyst	More localized form of dorsal enteric fistula
Diastematomyelia	Separation of cord into two hemicords
Caudal agenesis	Total or partial agenesis of spinal column
Segmental spinal dysgenesis	Various segmentation anomalies

extradural meningeal cyst containing neural tissue, e.g. Tarlov cyst and type III: spinal intradural meningeal cysts or intradural spinal arachnoid cyst. The diverticula of dura and/or herniation of arachnoid through a dural defect are thought to be an etiology of the spinal meningeal cyst.

CONGENITAL SPINAL DEFORMITIES

Congenital spinal deformities are caused by congenital anomalies of the spine due to abnormal vertebral development and result in growth asymmetry. The vertebral anomalies may be present at birth, but the deformity resulted from an abnormal spinal curvature may not be diagnosed until later in life. These anomalies are divided into three major categories: scoliosis, kyphosis, and lordosis. Combinations such as lordoscoliosis and kyphoscoliosis are common.

Although there are many types of vertebral dysmorphology observed in congenital scoliosis, they result from abnormal segmentation of the vertebral precursors, called somites. A congenital spinal deformity has a very high frequency of associated anomalies both within and outside the spine. Up to 60% of patients have one or more associated anomalies.²⁰ The most common associated lesion is spinal dysraphism. The prevalence of dysraphic lesions is approximately 40%.²¹ Various other spinal abnormalities may be seen, including Arnold–Chiari malformation, Klippel–Feil anomaly, syringomyelia, diplomyelia and intraspinal tumors. These lesions may or may not be associated with a cutaneous hairy patch, a nevus or a detectable neurologic deficit. Urogenital and cardiac anomalies occur in 20% and 10–15% of cases, respectively. Studies have estimated a 30–60% incidence of additional abnormalities in children with an existing congenital spinal deformity.²² The main associated defects involve

the VACTERL syndrome. VACTERL is an abbreviation with each letter representing an associated defect; vertebral anomalies, imperforate anus, cardiac abnormalities, tracheoesophageal fistula, renal dysplasias, and limb malformations.²³ The patients with congenital spinal deformities should be evaluated for these associated anomalies.

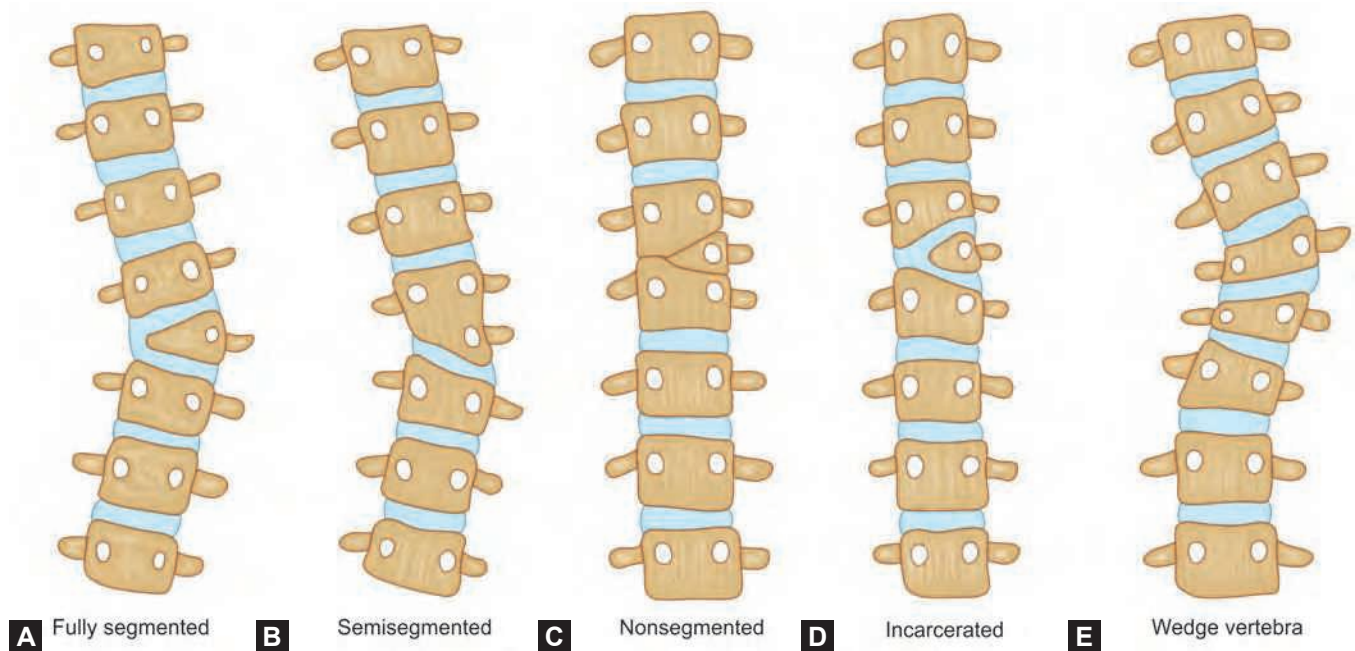
The interaction of environmental factors and the genes that play a role in regulation of somite segmentation is thought to be disrupted in congenital spinal deformities. The cycling of genes including notch pathway is thought to regulate the periodic activation of the notch signaling pathway, which would be required for the segmentation process. Mutations in two genes in the notch family have been identified with human defects of vertebral deformities; delta-like 3 in spondylocostal dysostosis,²⁴ and jagged 1 in Alagille syndrome.^{25,26} Spondylocostal dysostosis is a severe vertebral defect syndrome that is characterized by generalized vertebral anomalies, rib fusions, and congenital kyphoscoliosis. Alagille syndrome is a congenital, multiorgan disorder that is also associated with multiple vertebral anomalies and liver and heart problems. Somite genes that control or influence somitogenesis, including those in the notch family are currently

being examined in human spinal defects.⁴ Hypoxia, carbon monoxide, fetal alcohol syndrome, hyperthermia have been reported to be an environmental factor associated with congenital spinal deformities. The disturbances in the normal development of the spine that result in congenital spinal deformities may be caused by teratologic agents or can be on a genetic basis.

The congenital spinal anomalies result from either failure of formation, failure of segmentation, or a combination of abnormalities of the anlage of the vertebral column. The anomaly and where it is in the vertebral ring determine the deformity.

FAILURE OF FORMATION

The most common type of failure of formation anomaly is a hemivertebra. This is where a portion of the vertebra is missing resulting in a small, triangular shaped “half vertebra” or hemivertebra. Hemivertebra is a wedge-shaped vertebra with one pedicle. It can be subdivided as fully segmented, semisegmented, and unsegmented, according to the relation with the cranial and caudal adjacent vertebral bodies (Figs. 18.5A to E).



Figs. 18.5A to E: Failures of formation; various types of hemivertebrae and wedge vertebra. A hemivertebra represents a complete unilateral failure of vertebral formation. The hemivertebra may be fully segmented (A), semisegmented (B), nonsegmented (C) and incarcerated (D). Fully segmented or nonincarcerated hemivertebra have a normal intervertebral disc superior and inferior to the involved vertebral anomaly. Semisegmented hemivertebra is fused to the neighboring vertebra on one side with one open intervertebral disc space on the opposite side. Nonsegmented spaces superior or inferior hemivertebra are fused to both vertebrae with no intervertebral disc to the involved vertebral anomaly. An incarcerated hemivertebra is nested in a niche in a neighboring vertebra; the pedicle alignment remains straight, and a usual rule there is minimal scoliosis. A wedge vertebra represents a partial failure vertebral formation on one side (E).

Nakajima et al.²⁷ reported the types of laminae of formation failure and classified them into bilamina and hemilamina, based on the number of pedicles of the anomalous vertebra. Laminae with one pedicle are sub-classified into fully segmented hemilamina, semisegmented hemilamina, spina bifida, and incomplete lamina, which are defined as a nearly normal bilamina with only one pedicle.

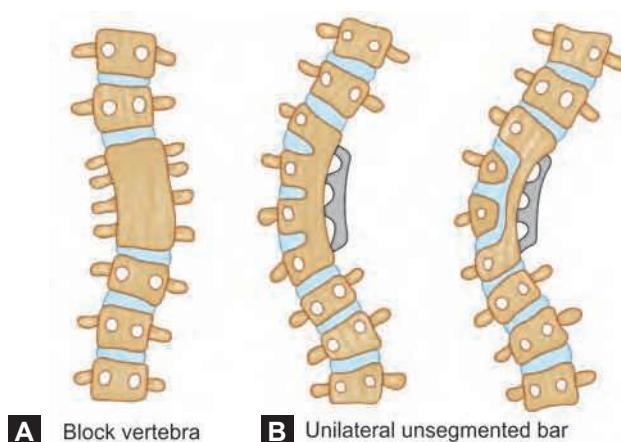
Wedge-shaped vertebrae result from partial unilateral maldevelopment, but there is usually an entire disc above and/or below. Wedge vertebrae are defined as wedge-shaped vertebrae with one pedicle on each side. Because wedge vertebrae exhibit two pedicles, they inevitably exhibit a bilaminar posterior structure. Kawakami et al.²⁸ proposed that wedged vertebra might be defined as a wedge-shaped vertebra in which the height of one side decreases by more than 50% of the opposite side, or whose adjacent cranial or caudal vertebra is almost normal shape, not wedge-shaped if the height on the one side of the wedge-shaped vertebra decreases less than 50% of the opposite side.

If the defect formation is symmetrical, several lesions are possible, including complete aplasia of the vertebra, aplasia of the vertebral body, or aplasia of the posterior elements. Complete or incomplete failure of midline fusions of the paired somites can result in butterfly vertebrae. Since, this type of anterior formation failure exhibits two pedicles, their posterior components are bilamina despite variations of the asymmetrical shape. An asymmetrical partial defect of the vertebral body often causes scoliosis.

Hemimetameric segmental displacement or shift is a multilevel pattern of vertebral anomalies characterized by two contralateral hemivertebrae separated by at least one normal vertebra.

FAILURE OF SEGMENTATION

Defective segmentation of the vertebrae can be symmetrical or asymmetrical. If a sclerodermal cleft fails to develop, fused vertebral bodies result. This may be unilateral, leading to an anterolateral bar, or bilateral, producing two blocked vertebrae, which are circumferentially unsegmented vertebrae. Unilateral unsegmented vertebral bars are caused by the failure of segmentation only on the left or right side of the spine. In the involved area of the spine there is absent or abnormal growth potential due to an area of missing bone (formation defect) or missing growth



Figs. 18.6A and B: Failures of segmentation; (A) block vertebra and (B) unsegmented bar. Block vertebra is a bilateral failure of segmentation with fusion of the intervertebral disc between the involved vertebrae. A unilateral unsegmented bar is a vertebral bar fusing both intervertebral disks and facets on one side; rib fusions are frequently present on the same side as the bar.

plates (segmentation defect). This results in an area of absent growth potential in the vertebral ring, and the growth in the remainder of the vertebral ring disrupts the normal alignment of the spine, producing different types of deformities (Figs. 18.6A and B). Unilateral unsegmented bar with contralateral hemivertebrae results from combination of abnormalities of the anlage of the vertebral column.

These anatomical changes of congenital spinal deformity have been classified by plain X-ray images, which were comprised mainly of vertebral bodies. The radiographic findings of front and lateral, plain X-ray images of congenital spinal anomalies sometimes result in difficulty in classifying the deformities when severe twisted three-dimensional (3D) curves are present. Kawakami et al. reported a new approach to 3D classification for congenital vertebral anomalies using the 3D CT images.²⁸ Analysis based on the perspective of 3D imaging might result in understanding the etiology and embryology. Careful individualized follow-up is necessary for the successful treatment of the patient with congenital spinal deformity.

CONGENITAL SCOLIOSIS

Congenital scoliosis is a lateral curvature of the spine caused by developmental vertebral anomalies that produce a lateral longitudinal imbalance in growth of the spine. Deformity can occur in any area of the spine, from the cervical to the lumbosacral region. The propensity for

progression is related especially to the type of anomaly, but also the growth rate of the patient. The most progressive type of scoliosis is that due to a unilateral unsegmented bar with a contralateral hemivertebra. The next most severely progressive type of curve is an isolated unsegmented bar, followed by scoliosis caused by two consecutive free hemivertebrae on the convex side.

CONGENITAL KYPHOSIS

Congenital kyphosis is defined as an abnormal sagittal curvature of the spine due to congenital vertebral anomalies that result in sagittal growth asymmetry. Failure of formation is usually included in the congenital kyphosis and nearly always occurs in the thoracic and thoracolumbar spine (Figs. 18.7A and B). More common are anterior symmetrical defects of segmentation, caused by failure of the mesoderm to cleft into somites and producing a congenital kyphosis (Figs. 18.7A and B). This type is most common in the lumbar and thoracolumbar areas.

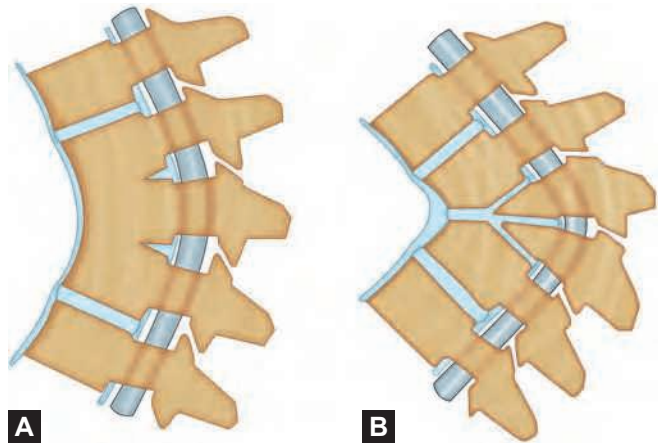
There are two types of spine dislocation—sagittal plane dislocation only and both sagittal and rotatory subluxation with subsequent rotatory displacement of the spinal canal²⁹—observed in congenital kyphosis, known as either congenital lumbar kypholisthesis, rotatory/congenital dislocation of the spine, or segmental spinal dysgenesis.

CONGENITAL LORDOSIS

Congenital lordosis, which is essentially always caused by failure of segmentation of the posterior arch structures in the presence of active growth anteriorly, is exceedingly rare. Most patients who have congenital lordosis also have some degree of scoliosis. The deformity associated with congenital lordosis is usually progressive. When the deformity occurs in the thoracic spine, it can severely compromise pulmonary function by markedly limiting intrathoracic volume.

CONGENITAL SPONDYLOLISTHESIS

Spondylolisthesis is from spondylos and listhesis, meaning movement or slipping, and refers to the slipping forward of one vertebra on the next caudal vertebra. Congenital or dysplastic spondylolisthesis is classified as type I (Figs. 18.8A and B).^{30,31} This is divided into following three types.



Figs. 18.7A and B: Type of congenital kyphosis. (A) Anterior failure of segmentation. (B) Anterior failure of formation.

Subtype IA

There is a congenital deficiency in the L5–S1 facet joints that allows forward slipping of L5 on S1. Hypoplasia or dysplasia of the superior sacral segment most commonly manifests as a combination of spina bifida occulta of S1 and deformity of the sacral articular processes. There is concomitant deformity of the inferior articular processes of L5. The inferior articular processes of L5 parallel the horizontally oriented sacral facets. This axial orientation and unstable anatomic situation may lead to forward slippage. There is no defect or elongation of the pars.

Subtype IB

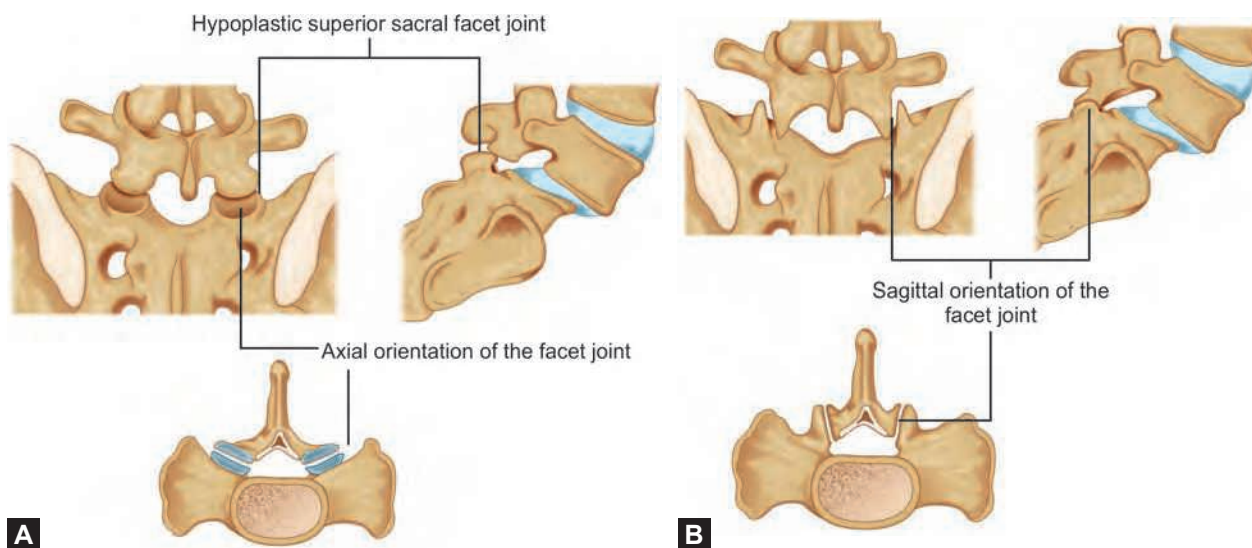
In this type, the articular processes have a sagittal mal-orientation, but the neural arch is usually intact. The intact neural arch usually prevents high degrees of forward slippage in this type. When the articular processes are sagittally oriented, there is no bone on bone contact in flexion. The soft tissues of joint capsules bear the force of flexion and allow forward subluxation. In some patients, in whom the articular processes are parallel to each other, may also allow spondylolisthesis.

Subtype IC

All other congenital anomalies of the lumbosacral junction are associated with spondylolisthesis. Congenital kyphosis is the most common anomaly.

CONGENITAL SPINAL STENOSIS

Congenital stenosis is present at birth as part of a malformation and divided into idiopathic and associated with a



Figs. 18.8A and B: Congenital spondylolisthesis. (A) Type IA congenital spondylolisthesis where the facet joints have a horizontal orientation, making them ineffective at preventing forward displacement of the lumbar vertebra above. (B) Type IB congenital spondylolisthesis caused by the articular processes having a sagittal malorientation.

developmental disorder, such as achondroplasia, hypochondroplasia, Morquio's mucopolysaccharidosis, and Down's syndrome. Congenital spinal stenosis often is asymptomatic until middle age, when secondary degenerative changes develop. The sagittal diameter of the lumbar spinal canal has its maximum development between 12th and 32nd week of intrauterine life and at birth has already reached 70% of its normal grown-up dimensions at the L1-L4 level. Therefore, prenatal factors influence the growth of the spinal canal. Generally, congenital stenosis is caused by an anomaly in the vertebral arch such as malorientation of the facet joints, hypoplasia of the laminae or pedicles. Congenitally, stenotic patients have a shorter pedicular length and as a result a smaller cross-sectional spinal canal area, compared with asymptomatic age- and sex-matched subjects. However, congenital lumbar stenosis has not been clearly defined radiographically.³² In achondroplasia, the vertebral disproportion is caused by a premature fusion of the vertebral body's chondrification centers with those of the vertebral arch, during the embryo's development. This results in a reduced bony spinal diameter.

CONCLUSION

This chapter has focused on anatomy of congenital spinal anomalies, which may be associated with development of the spine. Physicians should be aware of these common

types of congenital spinal anomalies as well as identify possible associated abnormalities in other systems thorough physical examination.

KEY POINTS

- Anatomies and some physiologies of congenital spinal lesions, which are involved congenital malformations of the spine and spinal cord caused by congenitally anomalous vertebral development, were reviewed.
- Physicians treating patients with congenital spinal lesions should have an understanding of normal embryologic development as well as common associated abnormalities.
- As congenital cervical lesions, the anatomy and physiology of basilar impression, occipitalization of the atlas, congenital stenosis, Arnold-Chiari malformation, congenital anomalies of the atlantoaxial joint and odontoid and KFS were reviewed.
- Anatomies and categorization of spinal dysraphisms are summarized in this chapter.
- Congenital spinal deformities are caused by congenital anomalies of the spine due to abnormal vertebral development and result in growth asymmetry. A new classification of congenital scoliosis based on the perspective of 3D imaging is needed to understand the etiology and embryology, as well as to determine an operative strategy.

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This is an excellent review of the current literature on the embryology of the spine and associated congenital abnormalities.

Watanabe M, Toyama Y, Fujimura Y. Atlantoaxial instability in os odontoideum with myelopathy. *Spine*. 1996;21:1435-9.

This article clearly demonstrated that sagittal plane rotation angles, or the instability index correlated with neurological signs and symptoms in patients with os odontoideum. The authors point out that it is important to evaluate the instability in congenital anomalies of the odontoid.

Samartzis DD, Herman J, Lubicky JP, et al. Classification of congenitally fused cervical patterns in Klippel-Feil patients: epidemiology and role in the development of cervical spine-related symptoms. *Spine*. 2006;31:E798-804.

The authors demonstrated that specific fused patterns of the cervical spine in patients with KFS were associated with cervical spine-related clinically significant symptoms, and that axial symptoms of neck/headache, neck pain,

and neck stiffness are the predominant symptoms in symptomatic KFS patients and are largely noted in patients who present with a single fused cervical segment.

Rufener SL, Ibrahim M, Raybaud CA, et al. Congenital spine and spinal cord malformations—pictorial review. *Am J Roentgenol*. 2010;194:S26-S37.

This article showed beautiful pictures of spinal dysraphisms in the text and the categorization is easy understandable.

Kawakami N, Tsuji T, Imagama S. Classification of congenital scoliosis and kyphosis. A new approach to the three-dimensional classification for progressive vertebral anomalies requiring operative treatment. *Spine*. 2009;34:1756-65.

The authors reviewed three-dimensional (3D) computed tomography (CT) images of congenital spinal deformities and proposed a new classification based on the information obtained. They clearly illustrate the limitations of two-dimensional classification, to summarize the clinical significance of 3D analysis of congenital vertebral anomalies, and to propose a new 3D classification of congenital vertebral anomalies.

Congenital Anomalies of the Cervical Spine

Paul Klimo Jr, Jonathan Reding, Nelson Astur, Melvin D Helgeson, Michael S Muhlbauer

Snapshot

- » Epidemiology of Congenital Disorders
- » Embryology and Development of the Cervical Spine
- » Craniovertebral Junction Abnormalities
- » Subaxial Spine Abnormalities
- » Syndromes

INTRODUCTION

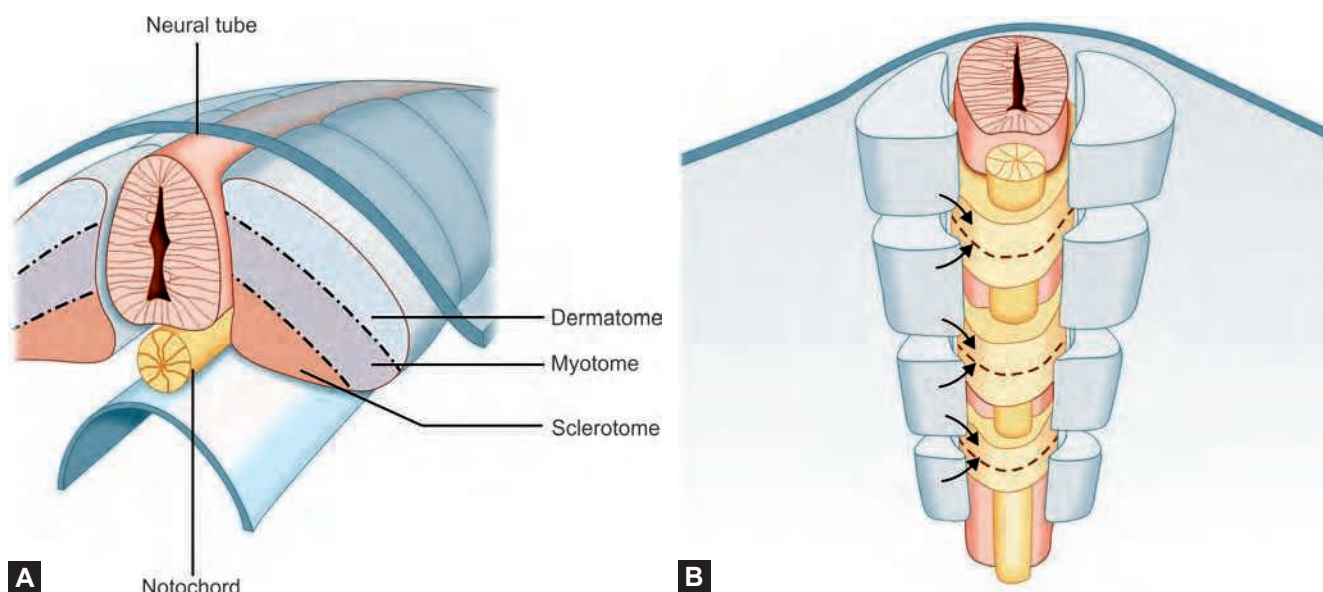
Congenital abnormalities of the cervical spine are variable in their clinical presentation, extent of anatomic malformation, and potential consequences for the patient. Most lesions are identified before adulthood, but some remain undetected until later in life. They can be asymptomatic and discovered incidentally; present with neck deformity, pain, neurologic symptoms; or present with acute or chronic myelopathy. They can be found in isolation as sporadic, solitary cases, or in combination with other cervical anomalies. Patients with genetic syndromes will have other spinal, skeletal, or multiorgan anomalies. Not infrequently, cervical anomalies may initially be misinterpreted as a traumatic injury (but will eventually be differentiated with the use of additional detailed imaging studies) in conjunction with a lack of soft tissue swelling and acute neurologic deficits and lesser degrees of vertebral subluxation.^{1,2} Treatment is also variable, ranging from no intervention to continued clinical and radiographic vigilance to urgent attention. Surgical intervention is typically reserved for those patients whose lesions are causing or have caused neurologic injury, chronic pain, or spinal deformity or whose injuries place them at high risk for developing any of these consequences. Treatment is also dependent on the age of the patient, his or her level of activity, and osseous development as it pertains to surgical fixation.

This chapter will focus on providing the reader with a comprehensive review of the numerous congenital osseous

anomalies of the cervical spine as they occur in isolation, with other anomalies, and as part of a syndrome. In addition, we will summarize the key steps in embryologic development of the different regions of the cervical spine. Treatment and outcomes will be briefly discussed where appropriate, but detailing the technical nuances and outcomes of surgical treatment for the various disorders is beyond the scope of this chapter. Furthermore, we will not discuss congenital anomalies that are more related to the development of the spinal cord,³ such as dermal sinus tracts,³⁻⁵ neurenteric cysts,⁶ myelocystoceles,⁷ and meningoceles,⁸ but will provide the reader with several references and emphasize that it is not uncommon for spinal cord and spinal column anomalies to coexist.

EPIDEMIOLOGY OF CONGENITAL DISORDERS

The incidence of congenital disorders is difficult to quantify because many congenital abnormalities of the cervical spine are asymptomatic and the true incidence is likely to be largely underreported. It has been estimated that as many as 5% of fetuses have vertebral anomalies, but the reported incidence in the general population is much lower.⁹ Some authors have reported that congenital anomalies of the cervical spine occur in approximately 1 in 40,000–42,000 births with a slight female predominance.^{10,11} Congenital fusions can occur at any level of the



Figs. 19.1A and B: (A) The ventral aspect of the somite is the sclerotome that becomes an aggregate of cells destined to become the skeletal system. (B) The process of resegmentation forms the vertebral body when the rostral half of one somite migrates and joins with the caudal half of the somite above.

cervical spine, although 75% occur in the region of the first 3 cervical vertebrae. The incidence of Klippel–Feil syndrome (KFS), which is described in greater detail later, is estimated to be approximately 1:40,000–42,000 births.^{10,12} Congenital fusion of the atlas with the occiput is one of the most common anomalies of the craniovertebral junction (CVJ), with a prevalence rate from 0.08% to 2.8% in the general population.¹³

EMBRYOLOGY AND DEVELOPMENT OF THE CERVICAL SPINE

Embryology is of paramount importance when it comes to understanding any type of congenital anomaly. The etiology of these disorders usually involves defects in some point of embryological development and malformation of tissues derived from all three embryologic layers. It is a highly complex process and is still not completely understood.

The human spine starts its embryological development on gestational day 16 while the embryo is within its triploblastic stage and shaped as a disk. The notochord is formed in the midline at the rostral end of the embryo by mesoblastic cells that migrate cranially from the primitive knot between the ectoderm and the endoderm. The presence of the notochord induces the overlying ectodermal cells to start the process of thickening and formation of the

neural plate. This plate's sides will then start to curl and, on day 21, will eventually fuse forming the neural tube, the future spinal cord. This process is called primary neurulation. The notochord and the primitive streak are strong inductive tissues and play a critical role in induction and development of future organs.

On either side of the notochord and the neural tube, mesodermal tissue condenses and—at about day 20—becomes segmented into four occipital and eight cervical somites, paired cuboidal structures arranged in consecutive fashion along the dorsal aspect of the embryo (Fig. 19.1A). The dorsolateral cells of the somite will become the dermomyotomes that will eventually give rise to the skin and the muscle. The ventromedial somite cells will become the sclerotomes; these are precursors of the skeletal system. Around day 35, the sclerotomes condense around the neural tube and the notochord. They will differentiate into a cranial and a caudal half, such that the rostral half of one somite migrates and joins with the caudal half of the somite above to form a vertebral body; this is a process known as resegmentation (Fig. 19.1B). The notochord starts differentiating and vanishing, eventually forming the alar and the apical ligaments at the C1–C2 levels, as well as the nucleus pulposus of the intervertebral disks. Chondrification begins at day 42 when centers appear on both sides of the small remnant of the notochord and coalesce toward the center. Centers also appear

laterally in each vertebral arch and propagate dorsally to form a cartilaginous arch. The chondrification proceeds dorsally to form the spinous process and then proceeds laterally to create the transverse processes. Within its cartilaginous template, ossification begins at day 72 with three primary ossification centers in a typical embryonic vertebra: one in the body and one in each of the vertebral arch halves. Secondary ossification centers start developing in the spine after puberty. There are five centers: one in the spinous process, one in each transverse process, and one ring of epiphysis in the superior and the inferior endplates of the vertebral bodies.

The embryology of the CVJ is unique and complex and deserves special consideration. The subaxial spine (C3–C7) can be considered a unit because each level exhibits the same developmental pattern.

Embryology of the Occipital Condyles

The proatlas is the resegmented sclerotome formed from the combination of the caudal half of the fourth occipital somite and the rostral half of the fifth somite (or first cervical somite). The proatlas forms the condyles, the basion, and the clival tubercle (or third occipital condyle or condylus tertius in some malformations), as well as the apical segment of the dens, and the apical, alar, and transverse ligaments of the dens.¹⁴

Embryology of the Atlas

The C1 resegmented sclerotome comes from the caudal half of the fifth somite (or first cervical somite) and the rostral half of the second cervical somite. The C1 vertebra is mainly formed from the C1 sclerotome: the anterior C1 arch from the hypochordal bow of the C1 sclerotome, and the rest from the lateral portion of the C1 (resegmented) sclerotome. C1 probably does not have contribution from the proatlas. C1 is the only vertebra to develop from only three ossification centers: one in each of its lateral masses and one in the anterior arch. The center in each lateral mass appears around the seventh week of fetal life while the anterior ossification center appears around the end of the first year after birth. Ossification of the posterior arch occurs during the seventh week of intrauterine life. A definitive fusion of the posterior arch of the atlas will only occur between 3 and 5 years of age. Later, between 5 and 9 years of age, the anterior center fuses with the two lateral mass centers.^{15,16}

Embryology of the Axis

The C2 resegmented sclerotome is derived from the caudal half of the sixth somite (or second cervical somite) and the rostral half of the seventh somite (or C3 cervical somite). The dens has contributions from three sclerotomes: the tip arises from the proatlantal sclerotome, the midportion from the first cervical sclerotome, and the base from the second cervical sclerotome. The second cervical sclerotome forms the lower portion of the dens, the centrum, and the dorsal arch of the axis. It has five primary ossification centers: two for the odontoid, two for the lateral masses, and one for the body (Fig. 19.2). The body of C2 fuses with the odontoid process by 3–6 years of age. This fusion line (i.e. subdental or dentocentral synchondrosis), or the remnant of the cartilaginous synchondrosis, can be seen until age 11 years and may be confused with a fracture. A secondary ossification center appears at the apex of the odontoid process (os terminale) between 3 and 6 years of age and fuses by age 12 years (Fig. 19.2).

Embryology of the Subaxial Cervical Spine

The resegmentation process continues throughout the subaxial spine. As stated previously, three ossification sites are present: the body, which arises from a single ossification site, and the two neural arches. The neural arches fuse posteriorly by the age of 2–3 years, and the body

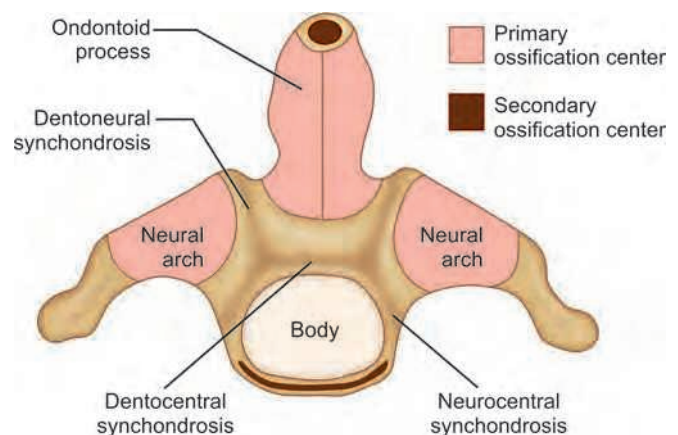


Fig. 19.2: There are five ossification centers in the axis, one within the vertebral body, two in the dens and one in each lateral mass/neural arch. The secondary ossification center forms at the tip of the dens around ages 6–8 and fuses with the dens around age 12. The dentocentral synchondrosis fuses by 3–6 years of life, but is still visible until 11 years of age and can be misinterpreted as a fracture.

fuses with the neural arches between 3 and 6 years of age. Additionally, secondary ossification centers may be seen at the tips of the transverse processes and the spinous processes that may persist until early in the third decade of life and simulate fractures. Secondary ossification centers can also appear at the superior and the inferior aspects of the cervical vertebral bodies and remain unfused until early adulthood.

■ CRANIOVERTEBRAL JUNCTION ABNORMALITIES

There are many developmental abnormalities that can occur at the CVJ. We refer the reader to the excellent detailed manuscript by Pang and Thompson.¹³ In general, these abnormalities can result in deformity, neural compression (of the cervicomedullary spinal cord and the lower cranial nerves) and vascular compromise, and can manifest with abnormal cerebrospinal fluid dynamics (e.g. hindbrain herniation or Chiari I malformations and syringohydromyelia). In a recent review of his extensive personal experience with children afflicted by craniovertebral anomalies, Menezes found that 80% had spastic quadriparesis, 30% had lower cranial nerve palsies, 40% had vertebrobasilar dysfunction, and 30–40% had hindbrain herniation.¹⁷ Hosalkar et al.¹⁸ evaluated 68 patients with 234 osseous upper cervical spine anomalies treated during a 15-year period. In 21 patients, the anomalies were associated with a syndrome and 79% of patients had three or more anomalies. Neck pain was present in 38% of patients; neurologic changes were present in 30%. Forty four (65%) patients eventually required decompression and fusion of the occipitocervical junction.

Malformations of the Occipital Condyles

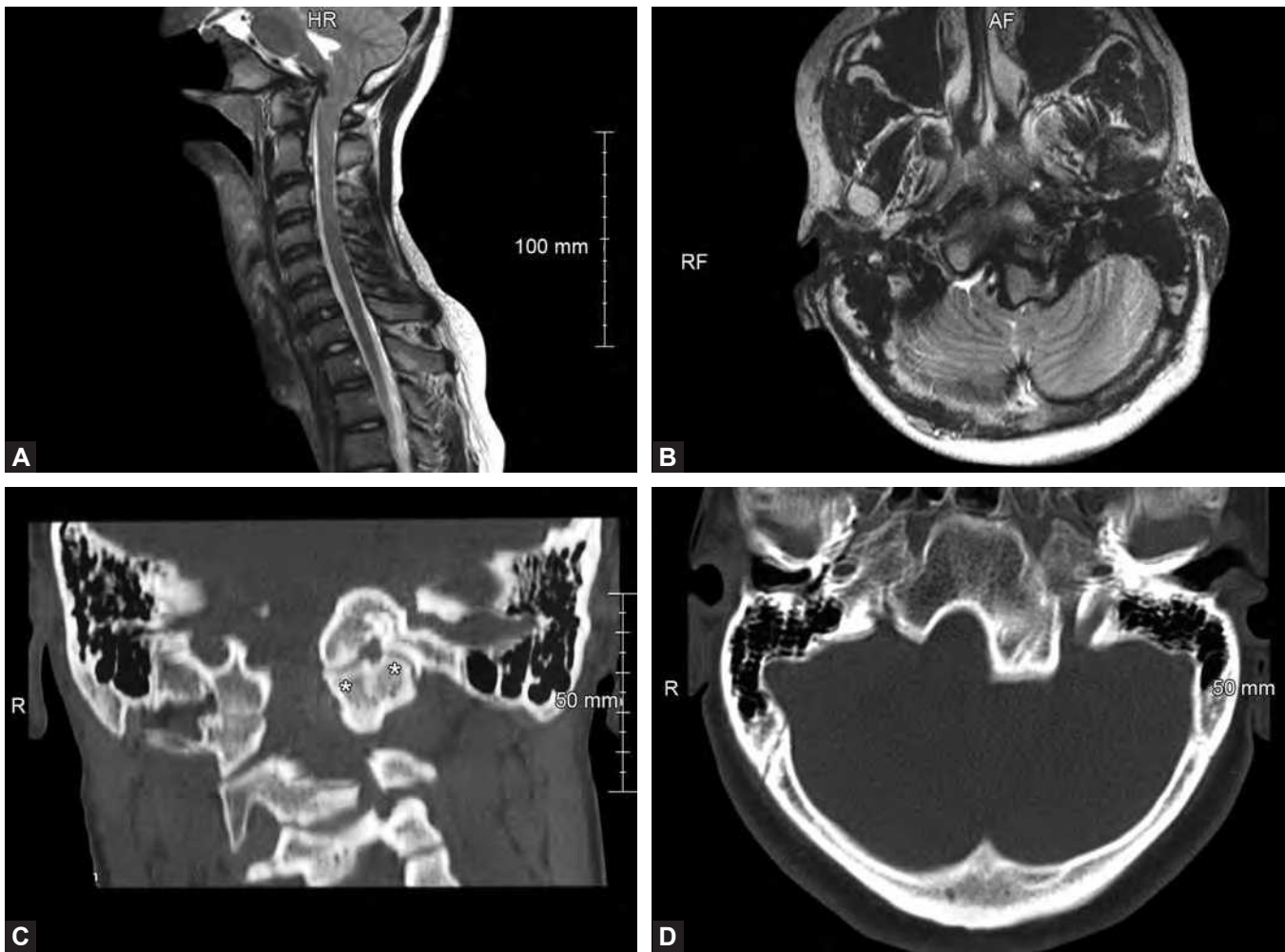
Duplications or irregular development of the occipital condyles are rare but have been reported.¹⁹ Condylar hyperplasia can be unilateral (i.e. “coconut” condyle) or bilateral and can result in a head tilt and cause myelopathy (Figs. 19.3A to D).^{20,21} Conversely, hypoplastic condyles are underdeveloped and have a flattened appearance and can lead to cranial settling and basilar invagination. A benign third condyle (or condylus occipitalis) has sometimes been discovered in the midline on autopsy.²² This third condyle is a small bony hunch on the anterior rim of the foramen magnum that articulates with the top of the dens or anterior arch of atlas. It is thought to represent a persistent hypochordal bow of the proatlas. A paracondylar process is

a bony exostosis that arises from the skull base just lateral to the occipital condyle and extends inferiorly toward the transverse process of the atlas. It usually has little or no clinical significance, or can be a source of occipitocervical pain that resolves with resection.^{23–26} Browd et al. have demonstrated that patients with Down’s syndrome and congenital occipitocervical instability fail to develop the curved architecture in the occipital condyle that occurs in age-matched controls over time (*see below*).^{27–29}

Occipitalization of the Atlas

Occipitalization—or assimilation of the atlas—occurs in approximately 0.25% of the population. It is characterized by fusion of the occiput to C1 and is generally defined as a failure of segmentation between the fourth occipital and the first cervical sclerotomes.^{30,31} The fusion can be complete, partial, unilateral, and either bony or fibrous (Fig. 19.4).³² Occipitalization of the atlas can occur with various syndromes, including achondroplasia, spondyloepiphyseal dysplasia (SED), Larsen’s syndrome, and Morquio’s syndrome. As such, it usually occurs in conjunction with other anomalies, such as congenital fusion of the second and third cervical vertebrae, basilar invagination, Chiari I malformation, and KFS, although it can be an isolated event.^{33,34} This anomaly is also associated with a high prevalence of anomalous vertebral artery position, which must be reviewed in detail before any surgery is undertaken. In fact, the frequency of vertebral artery anomalies at its extraosseous and intraosseous regions is increased in any patient having osseous anomalies at the CVJ. Tubbs et al.³⁵ found that there was an anomalous osseous pathway as the vertebral artery enters into the cranium in 80% of cadavers in which the posterior atlantal arch or hemiarch was fused to the occiput. A similar observation was reported by Yamazaki et al.³⁶ Abnormal courses of the vertebral artery at the extraosseous region were detected in 10 cases (two had fenestration and eight had a persistent first intersegmental artery), all of which occurred in their group of patients with atlantoaxial subluxation in conjunction with either an os odontoideum or occipitalization of the atlas. Also, 51.9% of these patients (14 out of 31) had a high-riding vertebral artery.

In most cases, the atlas and occiput are fused anteriorly with hypoplastic or anomalous posterior atlantal elements.^{30,37} Many of the afflicted patients are symptomatic, likely because of C1–C2 instability due to a weakened or absent transverse atlantal ligament from undue stresses and abnormal C1–C2 joint configurations.^{36,38,39}



Figs. 19.3A to D: Hyperplastic unilateral occipital condyle (i.e. “coconut condyle”) with platybasia. A 14-year-old male was referred to clinic with a slowly progressive myelopathy. The sagittal (A) and axial (B) magnetic resonance imaging show platybasia, tonsillar herniation and compression of the cervicomedullary junction. The coronal (C) and axial (D) computed tomography reveal a markedly enlarged and abnormal atlanto-occipital joint with what appears to be two separate joint surfaces (*).

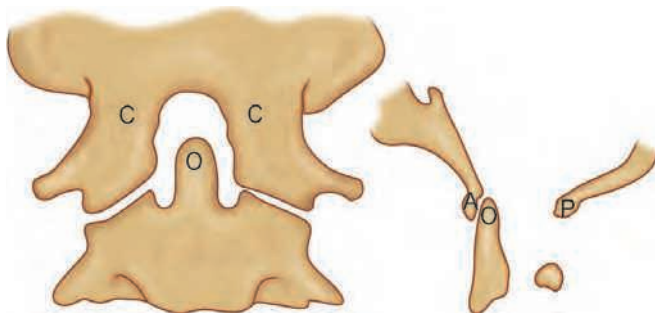


Fig. 19.4: An illustration showing a coronal and sagittal view of occipitalization of the atlas. The occipital condyles (“C”) are fused with the lateral masses of the atlas. The anterior (“A”) and posterior (“P”) arches of the atlas are fused with the basion and opisthion, respectively. “O” refers to the odontoid process.

Gholive et al.⁴⁰ recently provided a detailed radiographic and clinical analysis of 30 patients with occipitalization of the atlas. They categorized patients based on where along the atlas the fusion occurred, breaking down the locations of the fusions into three zones. Zone 1 assimilation involves the anterior atlantal arch in front of the lateral masses (20% in their series); zone 2 primarily involves the lateral processes (17%); and zone 3 is fusion at the posterior atlantal arch (13%). Fusions were relatively equally divided among zones, but those with fusions in the lateral masses had the highest prevalence of spinal stenosis (63%). Seventeen patients (57%) had atlantoaxial instability, which is related to the transferred stress (especially, flexion–extension) on the C1–C2 joint by the fusion of the occiput to C1.

The atlantoaxial segment can sustain a “double hit,” if there is also congenital fusion of the C2–C3 segment, which is not infrequent in these patients and was found in over half of Gholve et al.’s patients.^{17,40} These stresses can lead to a reducible form of basilar invagination. Because pannus (granulation tissue) can develop around the odontoid process as the body’s response to limit movement, the lesion becomes irreducible as the patient ages.^{17,41}

Neurologic symptoms in patients with occipitalization of the atlas include weakness, numbness or pain in the upper extremities, and associated upper motor neuron signs, including hyperreflexia and spasticity. Clinically, patients may present with a low hairline, restricted neck movements, and a short neck, all of which are also associated with KFS (*see below*).^{33,42}

Several treatment options are available for occipitalization of the atlas. If the anterior arch of C1 is fused to the occiput without associated translation of C1 relative to C2 (which may indicate an incompetent transverse ligament), the posterior elements of C1 can be resected. Associated atlanto-occipital or atlantoaxial instability should be treated with internal fixation and fusion. In some cases, the atlantoaxial subluxation or basilar invagination can be reduced by the use of traction and cervical extension. If the abnormality is reducible, posterior stabilization alone is adequate.^{43,44} If the spinal cord compression is inadequately reduced, ventral decompression with fusion and stabilization is required.⁴⁵

Atlantal Anomalies

Various congenital anomalies affecting the atlas have been reported either in isolation, with other anomalies, or as part of a syndrome. Absence of the anterior arch is an extremely rare anomaly and is thought to be due to aplasia of the hypochordal bow of the C1 sclerotome.^{46–48} Complete aplasia of the posterior arch of C1 and fusion of the C1 arch to the C2 have also been reported.^{49,50} Recently, an extremely rare case of unilateral enlargement of an atlas facet resulting in cord compression and progressive quadriplegia has been described.⁵¹

Various defects of the posterior ring of C1 have been described.^{52,53} According to the classification of Currarino et al.,⁵² there are five types of anomalies (Fig. 19.5): Type A defects are defined as failure of the two hemiarches to fuse at the posterior midline (i.e. failure of the two lateral ossification centers to unite posteriorly in the midline); Type B, unilateral clefts, ranging from a small defect to a complete absence of one hemiarch; Type C, bilateral clefts

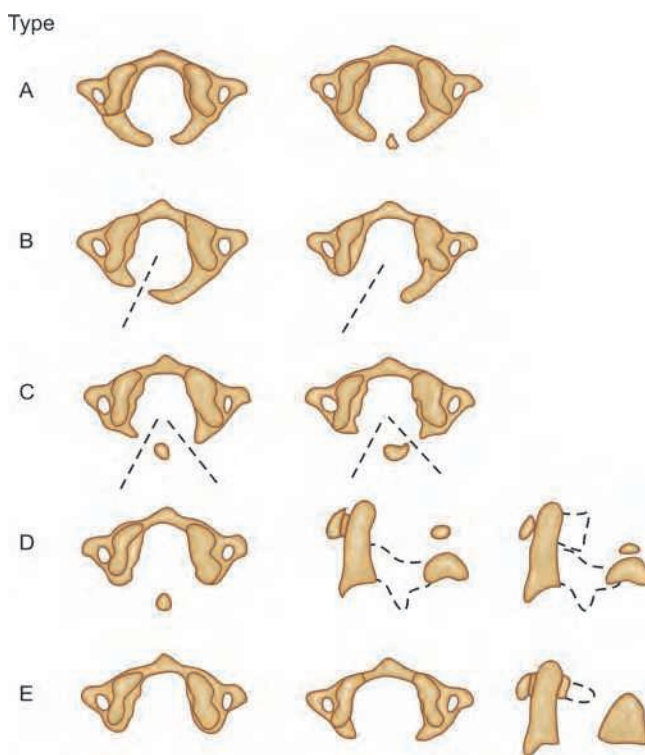
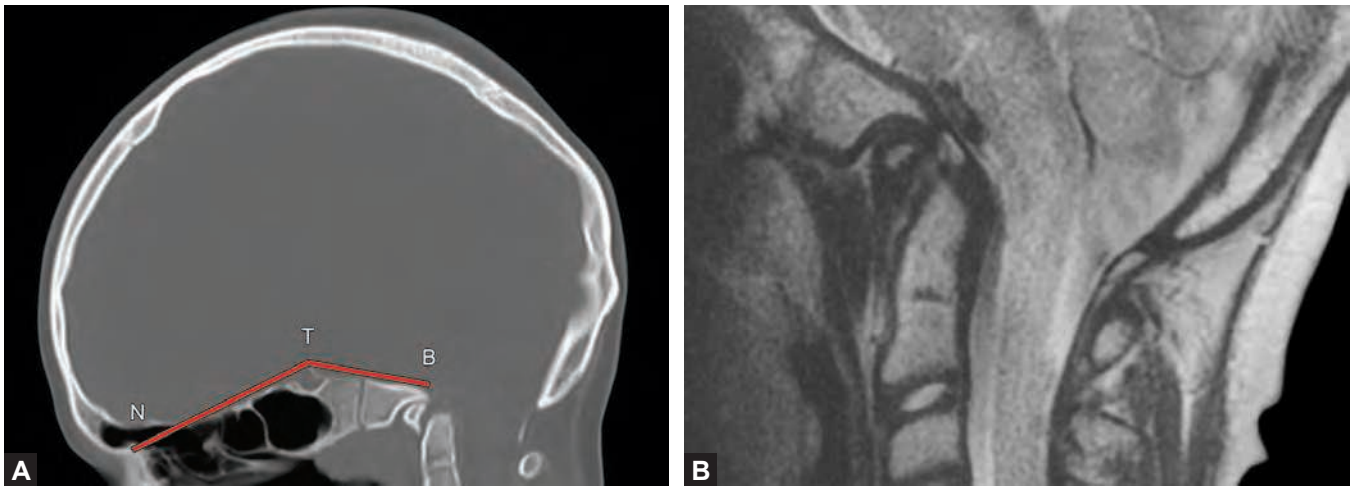


Fig. 19.5: The five different types of posterior atlantal arch defects, as defined by Currarino et al.⁵² Type A: Failure of posterior midline fusion of the two hemiarches. Type B: Unilateral cleft. Type C: Bilateral cleft. Type D: Absence of posterior arch with present posterior tubercle. Type E: Absence of posterior arch and posterior tubercle.

of the lateral aspects associated with preservation of the most dorsal portion of the arch; Type D, the complete absence of the posterior arch with a persistent posterior tubercle; and Type E, the complete absence of the posterior arch and posterior tubercle.

Posterior anomalies are much more common than anterior anomalies. Over a period of 1 year, Senoglu et al. found 40 cases of posterior atlantal arch anomalies in 1,354 evaluated cases (2.95%), whereas they found only one anterior arch defect in 1,104 computed tomography (CT)-documented cases (0.1%).⁵⁴ Evaluation using CT is important because anterior or posterior ring anomalies can often be mistaken for fractures on plain film.^{2,55} These anomalies alone are usually without any clinical consequence, although they are sometimes associated with other anomalies or may themselves cause myelopathy.^{48,56–58}

Atlantal hemirings can cause craniocervical instability that can worsen with time. This anomaly may cause, alone or in combination, disruption of the condylar-C1 articulation and its associated capsular ligaments, disruption



Figs. 19.6A and B: Sagittal computed tomography (A) and magnetic resonance imaging (B) demonstrating basilar invagination, with the tip of the odontoid above the plane of the foramen magnum. This patient also has platybasia. This is defined by drawing a line from the nasion (N) to the tuberculum (T) and from the tuberculum to the basion (B). An angle $>130^\circ$ confirms platybasia.

of the C1–C2 joint, and possibly lack of transverse ligament integrity. As the child grows, the hemirings can migrate or “spread” laterally, leading to progressive deformity, pain, basilar invagination, and myelopathy. Brockmeyer et al.⁵⁹ reported 19 patients with hemirings with a mean age of 22 months at presentation. The mean subluxation between the occiput and C2 on flexion–extension films was 9 mm (range 2–20 mm). Ultimately, 13 patients underwent occipitocervical fusion, and surgery was recommended for four of the remaining six children.

Congenital partial aplasia of the posterior arch of the atlas is a well-described phenomenon in which a bony defect of the posterior arch of C1 is replaced with a dense fibrous band that is mobile and can repeatedly traumatize the posterior spinal cord.^{60–63} Hypoplasia or incurving of the posterior arch, which effectively decreases the space available for the spinal cord, can cause progressive myelopathy.^{64–67} Interestingly, many patients will not present until well into adulthood.^{68–73} Treatment consists of removing the posterior arch.

The arcuate foramen (also known as ponticulus posticus [which means “little posterior bridge” in Latin], foramen arcuale, and foramen atlantoideum posterius) is an anomalous ossification of the posterolateral surface of the atlas that creates a complete or incomplete bone encirclement of the V3 segment of the vertebral artery as it exits the transverse foramen of the atlas. It also houses the vertebral venous plexus and the suboccipital nerve.⁷⁴ It is present in 5–19.3% of individuals and the incomplete type is more common.⁷⁵ This anomaly is usually of no

importance except in patients who need instrumentation of C1, in particular, lateral mass screws. In these patients, identification of this anomaly is important to prevent vertebral injury during placement of the screws.⁷⁶

Basilar Invagination

Basilar invagination, or cranial settling, is characterized by the encroachment of the foramen magnum by the odontoid process resulting in impaction of the cervicomedullary junction (Figs. 19.6A and B). Primary or true congenital basilar invagination is frequently associated with other abnormalities, including atlanto-occipital fusion, hypoplasia of the atlas, hemirings of C1 with “spreading” of the lateral masses, Chiari I malformations, odontoid abnormalities, KFS, and achondroplasia.⁷⁷ Condylar hypoplasia elevates the position of C1 and C2 and often leads to basilar invagination. Acquired basilar invagination, or basilar impression, is caused by softening of the bone at the base of the skull due to osteoarthritis, Paget’s disease of bone, hereditary disorders of connective tissue (such as osteogenesis imperfecta and Ehlers–Danlos syndrome), Hurler’s syndrome, rheumatoid arthritis, tumors or infection.^{78,79}

Generally, basilar invagination can be defined by the amount of protrusion of the odontoid process through the foramen magnum. Although its diagnosis traditionally involved measuring various lines (e.g. Chamberlain’s, McRae’s or McGregor’s lines) or positions of bony landmarks relative to others (e.g. Clark’s method, vertical atlantoaxial index) from lateral radiographs of the cervical

spine, today these measurements are more of historical rather than clinical value.^{30,80} Overlying skull base structures may obscure the identification of the key anatomic structures needed to determine these various measurements and Riew et al.⁸¹ have demonstrated that no one method has high enough sensitivity or specificity for screening purposes. Sagittal CT and magnetic resonance imaging (MRI) are the most informative images to diagnose and determine the degree of basilar invagination.

Pang and Thompson describe three types of congenital basilar invagination.¹³ The first type, anterior basilar impression, results in platybasia in which the nasion-tuberculum-basion angle is increased and the sphenoclival block is severely flattened. This flattening causes the basion to move cephalad and the foramen magnum to be tilted in a lordotic fashion. Along with platybasia, the clivus is shortened and the dens is retroflexed and lordotic. In posterior basilar impression, the second type of basilar invagination, the dens elevates into the cranial cavity either through elevation of the occipital condyles and opisthion or as a result of hypoplastic, flat condyles. The opisthion often invaginates into the foramen magnum. Finally, the third type is the combined form in which basilar impression results from a retroflexed dens and posterior invagination of the opisthion.

Traction is generally used for the initial treatment of basilar invagination to reduce the compression of the neural structures by the odontoid. A posterior occipitocervical stabilization procedure can be performed to maintain the reduction. If the invagination cannot be reduced, a transoral decompression, followed by a posterior occipitocervical fusion, may be required.^{78,82-84} Patients with an associated Chiari malformation type 1 or 1.5 and syringomyelia require foramen magnum decompression with duraplasty in addition to dorsal craniocervical junction fusion.^{45,77,82} For those patients without a concomitant Chiari malformation, Goel suggests that the treatment should be directed at distracting and fixating the atlanto-axial joint that will thus reduce the basilar invagination.⁸⁵

Axis Anomalies

Although they are less common than defects of C1, posterior C2 arch defects are often more problematic because they must be differentiated from traumatic spondylolisthesis and persistent neurocentral synchondrosis.^{86,87} Defects are generally characterized by sclerosis of the fragments that separate on flexion and malformation or underdevelopment of the posterior arch of C2.⁸⁸ Trivedi et al.⁸⁹

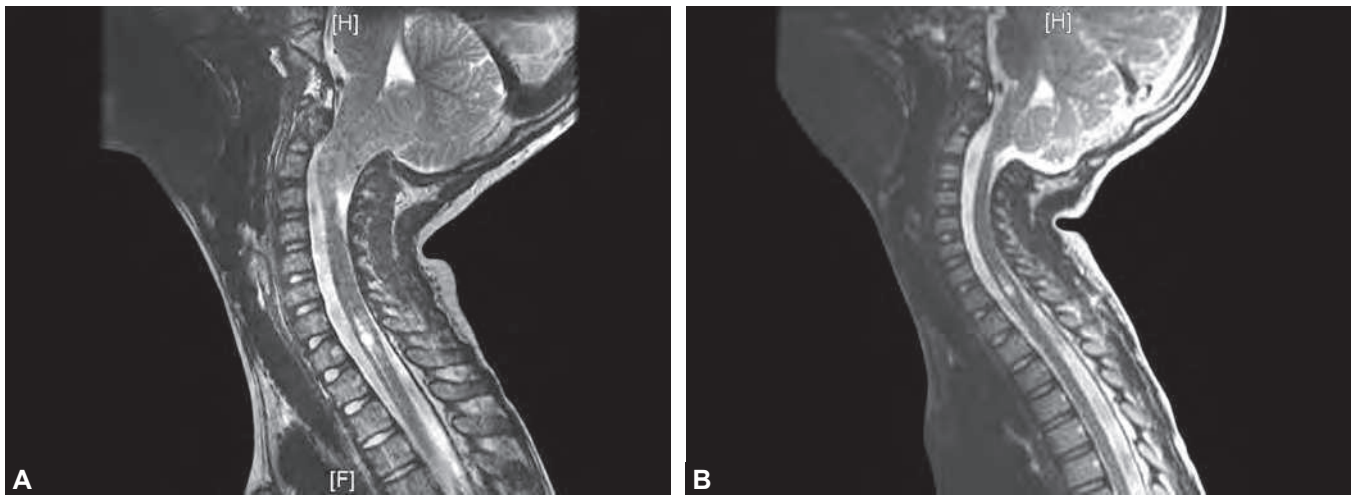
reported a case in which the patient had complete absence of the posterior elements of C2 and excessive motion between C2 and C3. The patient was treated with an occiput to C3 fusion. Spondylolysis of C2 is a rare diagnosis. It is described as a smooth and well-corticated defect or cleft between the C2 pedicles and the vertebral body. In contrast to subaxial spondylolysis described below, patients are usually younger; the vast majority are asymptomatic and less likely to have instability at C2–C3.⁹⁰

Dysplastic or hypoplastic posterior arches of C2 may cause myelopathy. The clinical and radiographic picture is similar to that of hypoplastic posterior arch of C1 in that the arch is often bifid and invaginating into the spinal canal and many patients present in adulthood. They, in fact, may be found in combination with atlantal anomalies.⁹¹ Treatment typically entails performing a laminectomy and fusion, if there is abnormal motion.⁹²⁻⁹⁴

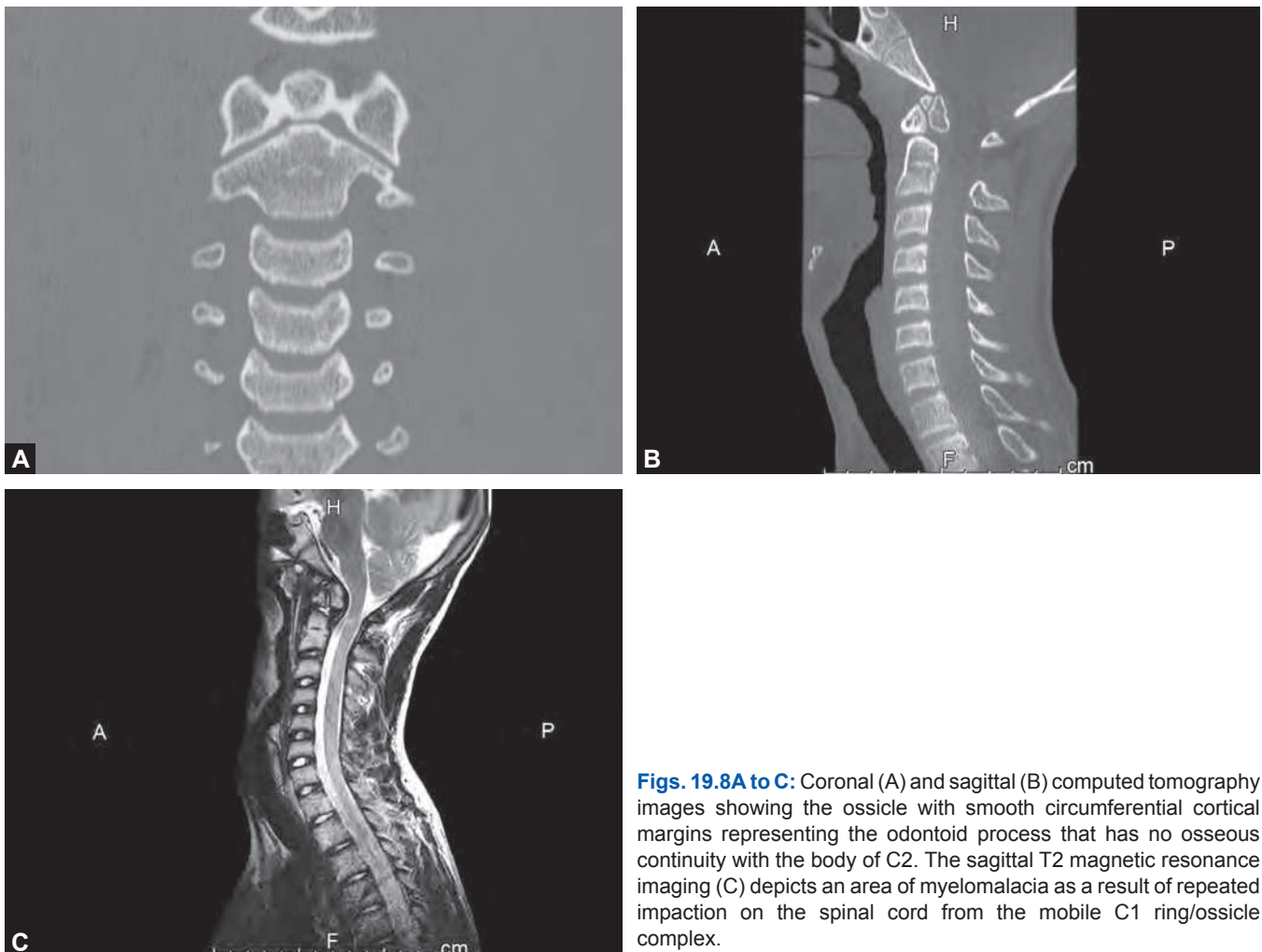
Anomalies of the Dens

There are a number of congenital abnormalities of the dens, primarily disordered formation, but also involving abnormalities of shape, which may result in atlanto-axial instability or compression of neurologic structures. Aplasia (agenesis) or hypoplasia of the dens is rare and usually found in syndromic patients (e.g. spondyloepiphyseal, Morquio's, Hurler's syndrome)⁹⁵; both aplasia and hypoplasia result in instability and require stabilization.⁹⁶ On the contrary, agenesis of the apical portion of the dens yields a shortened dens but does not cause instability. The odontoid may also be misshapen, angled posteriorly (retroflexed) in particular causing ventral brainstem compression and be associated with hindbrain herniation, as discussed previously (Figs. 19.7A and B). Tubbs et al.⁹⁷ found that a retroflexed odontoid was associated with syringomyelia; particularly, holocord syringes and higher grades of angulation were more common in female patients and with a greater degree of caudal displacement of the fourth ventricular obex. Transoral or transnasal resection of the retroflexed dens is required followed by posterior stabilization.⁹⁸⁻¹⁰⁰ A completely bifid or duplicate odontoid is exceedingly rare,¹⁰¹ in contrast to a dens bicornis in which only the tip is bifid and is of no clinical consequence.

Os odontoideum is a dissociation between the body of C2 and the dens, such that a disconnected ossicle takes the place of an intact odontoid process (Figs. 19.8A to C). The debate regarding the etiology of an os odontoideum continues with most feeling that there are both traumatic



Figs. 19.7A and B: (A) T2 Sagittal magnetic resonance imaging (MRI) showing a retroflexed odontoid, Chiari malformation and an associated syrinx. (B) MRI 6 months after suboccipital craniectomy and duraplasty with re-establishment of cerebrospinal fluid at the cervicomedullary junction and a smaller syrinx.



Figs. 19.8A to C: Coronal (A) and sagittal (B) computed tomography images showing the ossicle with smooth circumferential cortical margins representing the odontoid process that has no osseous continuity with the body of C2. The sagittal T2 magnetic resonance imaging (C) depicts an area of myelomalacia as a result of repeated impaction on the spinal cord from the mobile C1 ring/ossicle complex.

and congenital types.¹⁰²⁻¹⁰⁵ Furthermore, os odontoideum has been found in twins¹⁰⁶ and families,^{107,108} further strengthening the theory of a congenital etiology. Based on the position of the dens tip, two types of os odontoideum are described: orthotopic and dystopic. In the orthotopic type, the dens fragment lies in anatomic position and moves with the arch of C1. In dystopic os odontoideum, otherwise known as os avis, the ossicle is near or fused to the basion (clivus). The orthotopic type is much more common.

Dynamic imaging with flexion/extension films should be obtained to identify any instability and an MRI should be obtained to evaluate the spinal cord. The treatment of an unstable os odontoideum is a C1–C2 fusion.¹⁰⁹⁻¹¹¹ However, controversy exists with the management of a patient with an incidental or asymptomatic os odontoideum without radiographic instability. Some authors—including ourselves—have argued that even under these circumstances, virtually all patients should be offered fixation and fusion as the presence of an os odontoideum inherently creates an unstable atlantoaxial segment and places the patient at risk for a potentially catastrophic spinal cord injury with even minor trauma.¹¹²

It is important to differentiate an os odontoideum from an ossiculum terminale persistens. In the latter, the tip of the dens, the ossiculum terminale, fails to fuse with the remainder of the dens. The ossiculum terminale is usually much smaller than an os odontoideum and is firmly bound to the main body of the dens by cartilage. The ossicle lies at the level of the atlantal ring above the transverse atlantal ligament. Consequently, it is seldom the source of instability.

SUBAXIAL SPINE ABNORMALITIES

Anomalies of the subaxial cervical spine also occur but overall are less common than those found in the craniocervical junction. They can broadly be classified as disorders of either formation or segmentation and can be found in isolation or in combination with other spinal anomalies. Examples include midline vertebral body clefts, sagittal and coronal hemivertebrae, hypoplasia or complete absence of a vertebra, absence or malposition of a pedicle, hypertrophy of a lamina or spinous process, and block (or fused) vertebrae (most commonly found between C2 and C3).^{100,113-123} Radiographic characteristics typical of a congenitally absent cervical pedicle, which are almost always unilateral, are an enlarged ipsilateral neural foramen because of the absent pedicle; a dysplastic, dorsally

displaced ipsilateral articular pillar and lamina; and a dysplastic ipsilateral transverse process. Other osseous abnormalities are frequently associated with an absent pedicle and include spina bifida occulta, vertebral body or arch fusion, and additional hypoplastic pedicles.

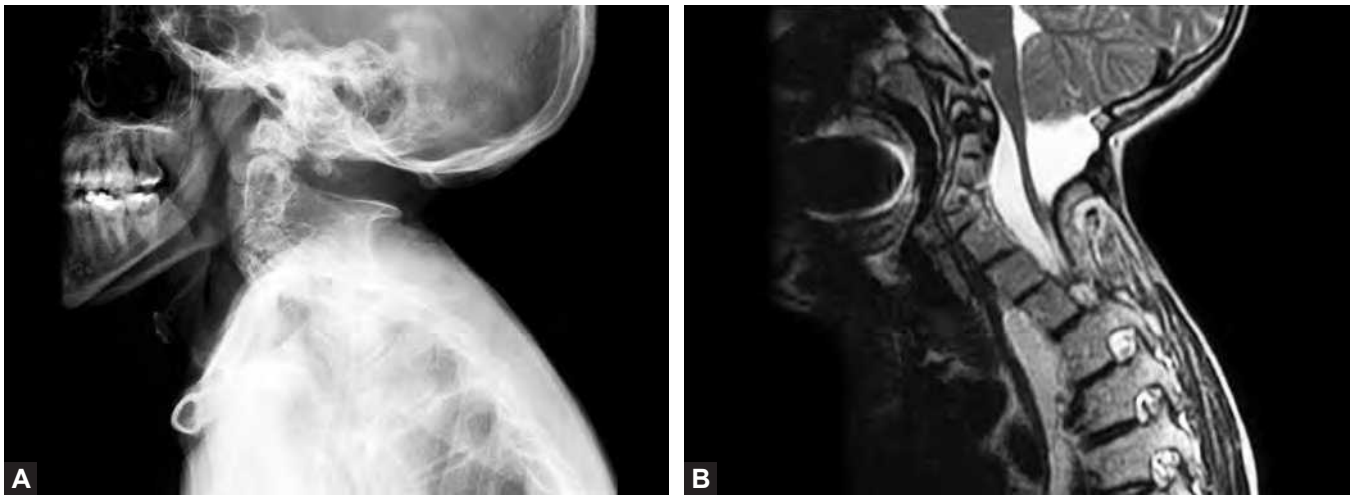
Cervical spondylolysis, which is a cleft between the superior and inferior articular facets of the articular pillar or lateral mass (it is the cervical equivalent of the pars interarticularis of the lumbar spine), is a rare congenital spinal anomaly.¹²⁴⁻¹²⁷ Characteristic radiographic findings include well-corticated margins at the defect, a characteristic “bow tie” deformity, and ipsilateral dysplastic facets. Compensatory hypertrophic changes of the adjacent articular processes, spina bifida, and spondylolisthesis are frequently seen.¹²⁸ The spondylotic cleft and spondylolisthesis give the appearance of posterior displacement of the dorsal pillar. Cervical spondylolysis most commonly occurs at a single level (the most common level is C6) with bilateral clefts, but multilevel and unilateral cases have been reported.^{124,125,129-132} This anomaly is typically discovered in adulthood and can present from asymptomatic to mild nonspecific neck pain and stiffness or radiculopathy but myelopathy unusual. Surgery is considered when there is excess motion or subluxation.

SYNDROMES

Numerous syndromes have cervical anomalies among their key features. We will briefly discuss the more common ones. More detailed descriptions can be found in several recent review articles.^{133,134}

Klippel-Feil Syndrome

In 1912, Klippel and Feil reported the case of a patient with the triad of a short neck, low hairline, and limited neck mobility who was found to have only 12 discernible vertebrae on autopsy.¹³⁵ Klippel-Feil syndrome refers to any congenital fusion of the cervical spine of two or more cervical vertebrae, with the most common level being C2–C3 (Figs. 19.9A and B).¹³⁶ Despite the initial description, it is now recognized that fewer than 50% of patients with congenital fusion of the cervical spine will have the triad of classic characteristics.¹⁰ Torticollis, or neck webbing, is seen in only 20% of patients with KFS.¹³⁷⁻¹⁴⁰ Facial asymmetry may be associated with cervical spine anomalies and hearing loss can be present in up to 30% of patients with KFS.¹³⁹⁻¹⁴¹ Other associated syndromes include Wildervanck's, Rokitansky-Kuster-Hauser, or Goldenhar's syndromes.



Figs. 19.9A and B: (A) Cervical spine X-ray of a 20-year-old male with Klippel-Feil syndrome demonstrating Sprengel deformity, fusion of the anterior and posterior elements of C2-C3 and an isolated posterior tubercle of C1. (B) The MRI gives a clearer picture of the segmentation defects, the ossiculum terminale C3 and absence of the anterior C1 arch, and a thin cervical spinal cord surrounded by a large CSF space.

Other cervical abnormalities found in KFS include occipitalization of the atlas, basilar invagination, hemivertebrae, and scoliosis. Scoliosis, which occurs in up to 60% of KFS patients, is more likely in patients with fusion of the mid and the lower cervical spine region, multiple contiguous congenitally fused segments, and associated vertebral malformations (e.g. hemivertebrae).¹⁴² Risk factors for basilar invagination (i.e. an odontoid tip >4.5 mm above McGregor's line) include four or more segments that are fused, female sex, and coronal angulation (e.g. scoliosis) $>10^\circ$.¹⁴³ However, 4.5 mm or greater migration of the odontoid was not synonymous and the presence of symptoms was not statistically correlated with the amount of odontoid migration.

Numerous musculoskeletal anomalies are associated with KFS, the most common being scoliosis (usually congenital), which occurs in up to 60% of patients. Sprengel's deformity, a congenital elevation of the scapula, can be seen in 20–35% of patients with KFS. An osseous, cartilaginous or fibrous connection between the scapula and the lower cervical spine is present about 50% of the time. Recently, Mooney et al.¹⁴⁴ described an osseous structure extending from the medial scapula to the clavicle and occipital region of the skull associated with a Sprengel's deformity. The Sprengel's deformity is thought to arise from failure of descent of the scapula from the first embryologic cervical level to its normal position, just caudal to the first rib.¹⁴⁵ Other musculoskeletal anomalies include cervical

ribs, rib anomalies, and hemivertebrae. Cardiovascular abnormalities are reported to occur in up to 14% of patients with KFS. Genitourinary abnormalities are also associated with KFS, affecting up to 64% of patients with the most common manifestation being unilateral renal agenesis.^{138,146,147} Abnormalities noted in the renal system may point to abnormalities of the reproductive system, particularly in females.

The most common clinical presentation of KFS is limited range of motion, particularly lateral bending. However, if fewer than three cervical vertebrae are fused, motion of the cervical spine may appear normal because adjacent levels may compensate. Thus, patients with more extensive neck fusions may present at an earlier age. Similarly, higher fusions near the CVJ often present earlier with pain, whereas those with lower cervical fusion present later when symptomatic junctional degeneration develops.¹⁴⁸ Samartzis et al.¹⁴⁹ have shown that involved segments between C2 and T1 often become completely fused (demonstrating bridging bone both anteriorly and posteriorly) as children age. Conversely, the upper cervical segments do not show such a pattern. Instead, fusion of the posterior elements was more common than fusion of the anterior elements. The same authors also found that congenital fusion may arrest the normal vertebral development as these levels tended to have greater canal dimensions (i.e. space available for the cord) and the cephalad-to-caudal dimension of the vertebral bodies was less.¹⁵⁰

Neurologic disturbances associated with KFS include developmental abnormalities of the central nervous system (such as brainstem malformations), myelopathy as a result of long-standing spinal cord compression, radiculopathy as a result of nerve root irritation, and nonspecific symptoms of headache, weakness, and numbness. Up to 20% of patients with KFS will exhibit synkinesis in which involuntary mirrored motions, primarily in the upper extremities, are observed.^{151,152} The cause is unknown, but autopsy results of two patients with KFS and synkinesia showed an incomplete pyramidal decussation. Synkinesia is generally effectively treated with occupational therapy, and the condition often subsides as the patient ages.

Routine plain radiography can quickly identify an obvious congenital fusion or cervical stenosis. Flexion and extension views provide a dynamic snapshot to identify instability of the atlanto-occipital, atlantoaxial, and subaxial joints, although radiography of the cartilaginous spine of children younger than 8 years of age can be difficult to interpret. Magnetic resonance imaging should be used in the setting of suspected compromise of the brainstem or the spinal cord and to detect other central nervous system lesions, such as syringomyelia, tethered cord, diastematomyelia, and Chiari malformation.^{10,153} Further imaging of the thoracic and lumbar spine is warranted in patients with KFS to identify abnormalities in these regions.¹²

Because many patients are asymptomatic throughout life, treatment for KFS must be individualized. For patients with atlanto-occipital instability, occipitocervical fusion should be performed.⁴³ Atlantoaxial instability is best approached with C1–C2 transarticular screw fixation techniques. Patients with subaxial instability typically will not present with neurological symptoms but may have significant degenerative disc disease. Subaxial fusions may place additional strain on the adjacent motion segment leading to premature disc degeneration. These patients may be successfully treated with discectomy and fusion. Symptomatic cervical stenosis over multiple levels is generally treated with posterior decompression and fusion.^{154,155}

Down's Syndrome

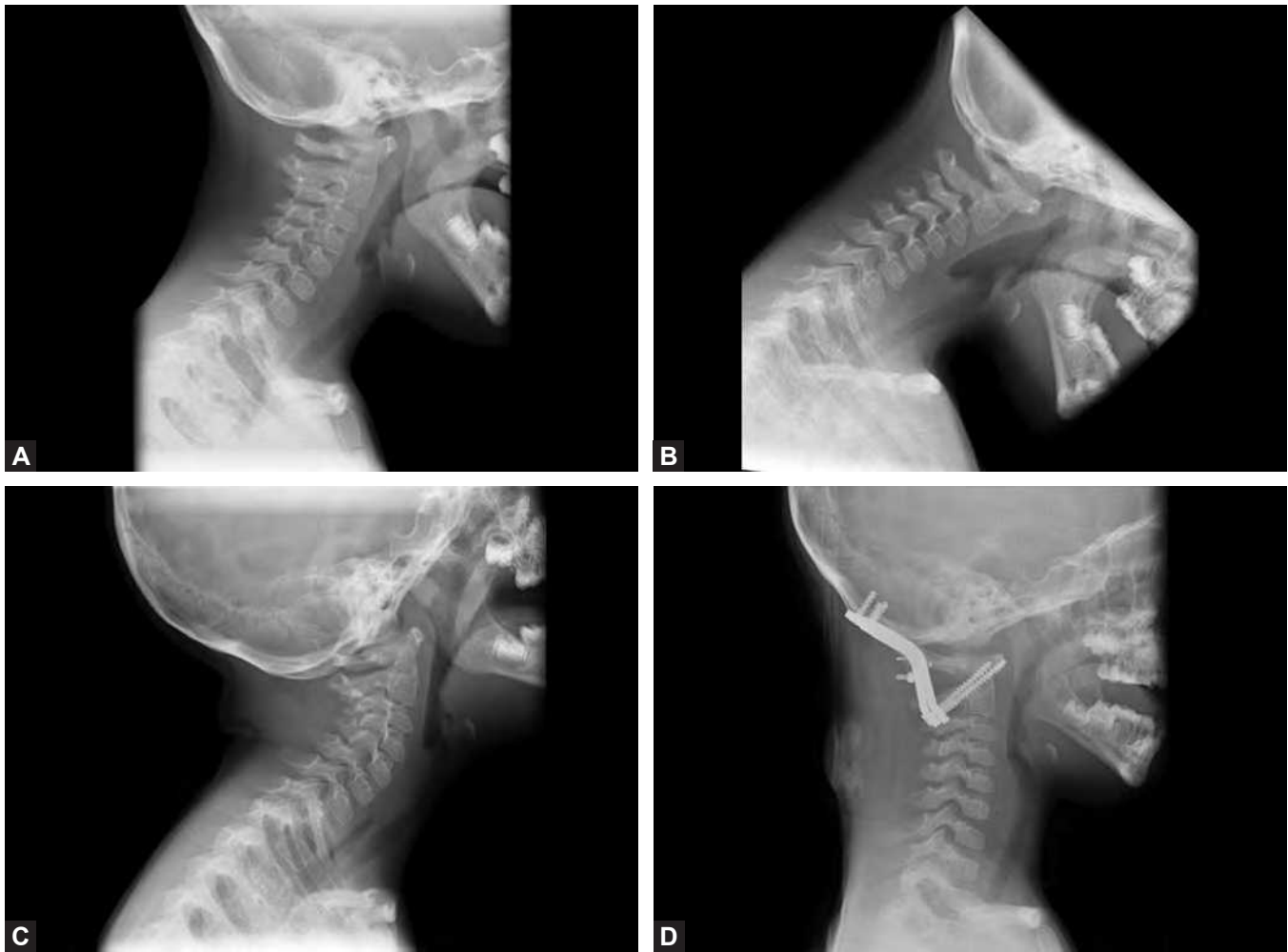
Down's syndrome, or trisomy 21, is the most common inherited chromosomal disorder in humans. The craniovertebral joints may be unstable in these patients for a variety of reasons (Figs. 19.10A to D). Lack of a concave C1 superior articulating surface in conjunction with a

failure to develop the curved architecture in the occipital condyle results in a flat or "rocker bottom" joint.^{27,28} Down's syndrome patients frequently have atlantoaxial joint instability as a result of a lax transverse ligament, the presence of an os odontoideum, or odontoid hypoplasia.¹⁰⁹ This instability has been a source of controversy relating to the participation of Down's syndrome patients in the Special Olympics. Since the early 1980s, the Special Olympics Inc. has defined atlantoaxial instability as an atlantodental interval (ADI) >4.5 mm. Any instability automatically disqualifies children from participating in the high-risk activities. However, this restriction can be waived if an acknowledgment of the risks is signed by an adult athlete; if the athlete is a minor, his/her parent or guardian signs this acknowledgment and two physicians must give written certification. These restrictions remain controversial since there has never been a reported case of an asymptomatic patient with atlantoaxial instability developing neurologic injury due to a sports-related injury.^{156,157} Pizzutillo and Herman proposed that patients with an ADI <4.5 mm can continue with unrestricted activity; those between 4.5 and 10 mm are at risk and should be kept from high-risk activity; those with an ADI >10 mm or any symptomatic patient with cord signal changes indicative of spinal cord injury should be fused.¹⁵⁸

Achondroplasia

Achondroplasia has a significant association with craniocervical deformities. A narrowed foramen magnum and upper cervical stenosis may be seen with CT and MRI in a majority of patients (Figs. 19.11A and B).^{159,160} Compression may result from hypertrophied margin of the foramen magnum, anterior extension of the squamous portion of the occipital bone into the foramen magnum, abnormal fusion of the posterior neural arch of the atlas with the posterior margin of the foramen magnum, or dense fibrotic epidural bands commonly found anterior to the posterior ring of the atlas. There has also been a case report of overgrowth of the opisthion into the foramen magnum.¹⁶¹ In patients with achondroplasia, the odontoid process often projects posteriorly and superiorly into the small foramen magnum, resulting in medullary compression.¹⁶²

Although foramen magnum stenosis is a common radiologic finding in pediatric achondroplasia patients, only a fraction of those patients will exhibit symptoms of cervicomedullary compression. For this reason, treatment decisions should be based on signs or symptoms of neurological dysfunction rather than on the radiological



Figs. 19.10A to D: This 3-year-old child with Down's syndrome had screening X-rays done prior to enrolling in a physical recreation program. Neutral (A), flexion (B) and extension (C) plain films demonstrate 8–9 mm of motion between the occiput and C1 and 3–4 mm widening of the atlantodental interval (ADI). (D) The child underwent an occipitocervical fusion.

evaluation alone. Treatment involves suboccipital decompression usually without duraplasty to accommodate the lower brainstem and upper spinal cord and is very successful at improving or completely resolving preoperative neurologic symptoms.¹⁶³ Duraplasty is often avoided because it is difficult to achieve a water-tight closure and many children have underlying hydrocephalus secondary venous hypertension from jugular foramen stenosis.¹⁶³

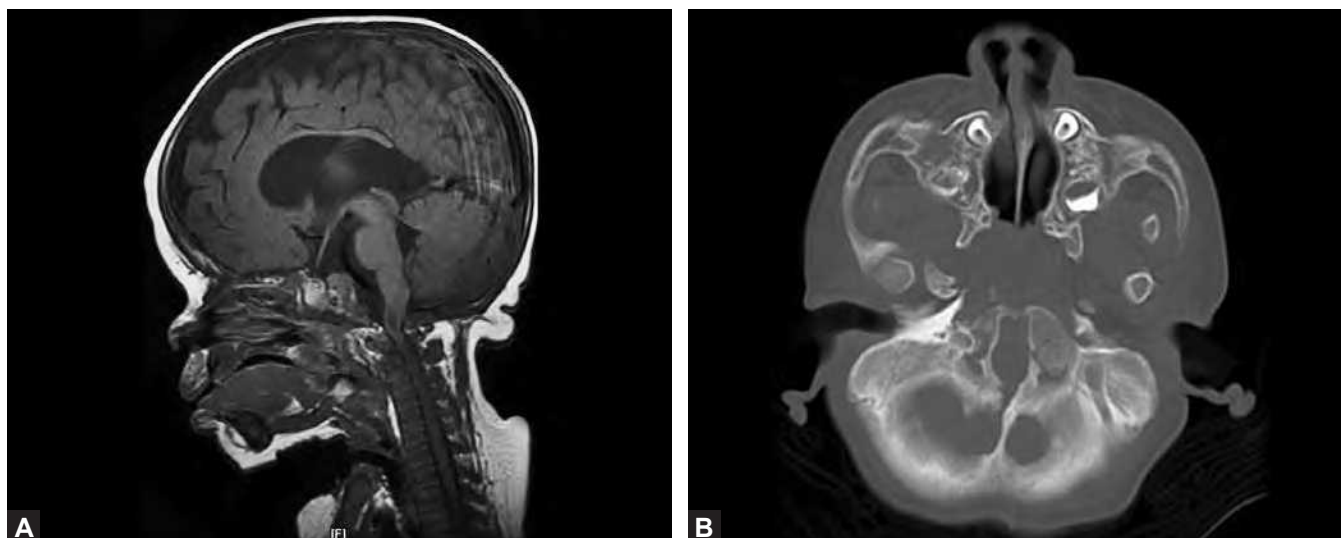
Larsen's Syndrome

The triad of distinctive facial features, dislocations of multiple joints, and spinal anomalies was first described by Larsen in 1950 in a series of his patients.¹⁶⁴ The spinal manifestations include scoliosis, spinal stenosis, abnormal

segmentation, neural arch defects, coronal cleft vertebrae, hemivertebrae, and anteroposterior dissociation. Dramatic midcervical multilevel kyphosis is often present and can lead to instability, progressive myelopathy, weakness, and even sudden death in Larsen's syndrome.¹⁶⁵⁻¹⁶⁷ For this reason, the cervical spine should be imaged immediately after a diagnosis of Larsen's syndrome has been made.

Goldenhar's Syndrome

Goldenhar's syndrome, also known as oculoauriculovertebral dysplasia, is a clinically diverse disorder characterized by hemifacial microsomia, epibulbar dermoid appendages, and spinal defects. Segmentation defects (i.e. block vertebrae) are common in the cervical spine, whereas



Figs. 19.11A and B: Images from an 8-year-old achondroplastic dwarf. (A) T1 Sagittal image shows severe stenosis of the foramen magnum along with hypoplasia of the dens and clivus. (B) The computed tomography confirms the narrowed foramen magnum with an ovoid rather than circular shaped foramen magnum, typical of achondroplastic patients.

formation defects (i.e. hemivertebrae) are more common in the thoracic spine, leading to scoliosis. Other anomalies include basilar invagination, retroflexed odontoid, assimilation of the atlas, and odontoid hypoplasia leading to atlantoaxial instability.^{168,169}

Spondyloepiphyseal Dysplasia

Spondyloepiphyseal dysplasia encompasses several disorders characterized by abnormal growth of the spinal vertebrae and epiphysis. Atlantoaxial instability, as a result of odontoid hypoplasia, and os odontoideum or transverse ligament laxity, is the most common spinal manifestation of SED in children.¹⁷⁰ In addition, the ring of C1 is small, which further compromises the sagittal canal diameter at this level.

Morquio's Syndrome

Mucopolysaccharidosis type IV (MPS IV), or Morquio's syndrome, is an autosomal recessive lysosomal storage disease characterized by an inability to metabolize keratan sulfate, a glycosaminoglycan found predominantly in cartilage and in the cornea. As in SED, the most common cervical manifestation is atlantoaxial instability due to odontoid dysplasia (hypoplasia, aplasia, os odontoideum) or ligamentous laxity.^{171,172}

Congenital Multilevel Cervical Disconnection Syndrome

Congenital multilevel cervical disconnection syndrome is a newly described syndrome in which there is an osseous disconnection between the anterior and posterior elements resulting in a severe kyphotic deformity and myelopathy, similar to what is found in Larsen's syndrome (see Fig. 19.4).¹⁷³ Patients require extensive anterior and posterior reduction, decompression, reconstruction, and stabilization/fusion procedures. The pathology is thought to be due to failure of chondrification centers in the centrum and dorsal arches to coalesce.

SUMMARY

Congenital anomalies of the cervical spine vary widely. Patients may present with abnormalities as simple as two congenitally fused vertebrae requiring no treatment, or as complex as craniocervical instability requiring occipito-cervical fusion. It is important to recognize that some of these malformations may be associated with other defects involving the cardiovascular, neurological, renal, and reproductive systems. The true incidence of these anomalies is not known for certain, partly because of their frequent asymptomatic nature. Recognizing those congenital abnormalities that can contribute to an unstable cervical spine or critical spinal stenosis may prevent a catastrophic spinal cord injury.

KEY POINTS

- Understanding the embryology of the cervical spine helps us to understand the development and progression of these anomalies.
- Congenital cervical anomalies can occur in isolation or in association with a syndrome.
- Congenital cervical anomalies can be asymptomatic or cause significant neurologic deficits.
- The true incidence of congenital cervical anomalies is likely largely unreported and difficult to quantify due to many asymptomatic patients.
- Craniocervical junction anomalies are more common and frequently require surgical stabilization.

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- Browd SR, McIntyre JS, Brockmeyer D. Failed age-dependent maturation of the occipital condyle in patients with congenital occipitoatlantal instability and Down syndrome: a preliminary analysis. *J Neurosurg Pediatrics*. 2008;2:359-64.

The purposes of this study was to establish normative data characterizing the shape of the occipital condyle in healthy children and compare these data with measurements collected in patients with congenital occipitoatlantal instability or Down's syndrome. The effectiveness of CT and plain radiography data were also compared.

- Gholve PA, Hosalkar HS, Ricchetti ET, et al. Occipitalization of the atlas in children. Morphologic classification, associations, and clinical relevance. *J Bone Joint Surg Am*. 2007;89:571-8.

Thirty children with occipitalization were studied with computed tomography and/or magnetic resonance imaging and a description of their clinical characteristics. A new morphologic classification of occipitalization was developed based on four patterns according to the anatomic site of occipitalization (zones 1, 2, and 3 and a combination of those zones), each of which may have different prognosis implication.

- Brockmeyer DL, Brockmeyer MM, Bragg T. Atlantal hemirings and craniocervical instability: identification, clinical characteristics, and management. *J Neurosurg Pediatr*. 2011;8:357-62.

The authors present a series of 19 patients with atlantal hemirings, a disorder resulting in congenital craniovertebral instability. Presentation, treatment, imaging, and follow-up data obtained in patients with atlantal hemirings were assessed to identify factors relevant to craniocervical instability. The authors believe that this anomaly is the underlying cause of progressive instability in a significant proportion of patients with craniocervical abnormalities. The presence of atlantal hemirings should prompt immediate and thorough neurosurgical evaluation.

- McKay SD, Al-Omari A, Tomlinson LA et al. Review of cervical spine anomalies in genetic syndromes. *Spine (Phila Pa 1976)*. 2012;37:E269-77.

The literature was reviewed for cervical spine issues in 10 specific syndromes. The information is presented in the following order: First, the identification and treatment of midcervical kyphosis in Larsen's syndrome and diastrophic dysplasia. Next, the upper cervical abnormalities seen in Down's syndrome, 22q11.2 deletion syndrome, pseudoachondroplasia, Morquio's syndrome, Goldenhar's syndrome, spondyloepiphyseal dysplasia congenita, and Kniest dysplasia. Finally, the chin-on-chest deformity of fibrodysplasia ossificans progressiva.

Congenital Anomalies of the Spinal Cord

G Balamurali, S Rajasekaran

Snapshot

- » Epidemiology
- » Pathogenesis
- » Clinical Evaluation
- » Abnormalities
- » Split Cord Malformation
- » Dermal Sinus, Dermoid, and Epidermoid Cysts
- » Sacral Agenesis and Caudal Regression Syndrome
- » Syringomyelia and Chiari Malformation
- » Tethered Cord Syndrome

INTRODUCTION

Anomalies of the spine and the spinal cord are often collectively termed spinal dysraphisms. The term “spinal dysraphism” encompasses a heterogeneous group of congenital spinal anomalies where the midline structures fail to fuse early in fetal life and other anomalous development of the caudal cell mass. Malformation of spinal cord may occur in isolation or can be associated with anomalies in the bony spine, nerve roots or covering membranes, or viscera as all these structures develop at the same time.¹

The true incidence of spinal dysraphism is still unclear and is probably underestimated. However, there is a decline in incidence in the last two decades due to various factors, which include better nutrition in women, timely supplement of folate, and better prenatal diagnosis of abnormalities. Spinal dysraphism can be classified as closed or open, depending on whether the overlying skin is intact or deficient. The closed form of spina bifida is termed spina bifida occulta, where the defect is well covered with full thickness skin. They are mostly diagnosed incidentally. The open forms that include myelocele, meningocele, and myelomeningocele are often associated with hydrocephalus and Arnold–Chiari malformation type II and may be classified as spina bifida aperta.

EPIDEMIOLOGY

Spina bifida occulta occurs in about 20–30% of the total population. In isolation, it is often an incidental finding and usually of no clinical importance. However, it may occasionally be associated with diastematomyelia, tethered cord, lipoma, or dermoid tumor. In the presence of occult spina bifida, >90% of patients have a tethered cord,^{2,3} approximately 23.7% have a dermal sinus,¹ and caudal regression syndrome accounts for 16.3%.¹ There is usually an overlying cutaneous manifestations including lipoma, hemangioma, cutis aplasia, dermal sinus, or hairy patch.

Open Spinal bifida is a midline congenital defect with a reported incidence of 2–4/1,000 live births.¹ Myelomeningocele accounts for 98.8% of the open spinal dysraphisms.^{4,5} Females are affected slightly more often than males, with the firstborn being usually affected more often. The most common locations for these malformations are, in decreasing frequency, lumbosacral, thoracolumbar, and cervical spine.^{5,6} In the recent years, the true incidence of myelomeningocele has varied geographically from region to region based on their diet, fortification of food with folic acid supplements, education and awareness levels, availability of prenatal diagnosis, and elective termination.^{7–9} Patients with open spinal dysraphism almost always have associated Chiari II malformation. Myelocele is a rare malformation and represents

only 1.2% of all open spinal dysraphisms.⁵ Sacral agenesis occurs in approximately 1 per 7,500 births without a gender predisposition. In the normal adult population, the conus terminates at L2 level in 95% of cases.^{9,10} Tethered cord implies low-lying conus, but tethered cord may occur in the presence of conus in normal position.⁹⁻¹⁵ Up to 15% of patients with repaired myelomeningoceles will experience a secondary tethered cord syndrome (TCS) later in life.¹⁶

PATHOGENESIS

Chapter 17 deals with the normal embryology and development of the spine and the spinal cord. Spinal cord embryological development occurs through *three consecutive periods* gastrulation, neurulation, and caudal regression.^{5,9,10,17-19} The trilaminar embryo composed of endoderm, mesoderm, and ectoderm develops by day 18 of gestation. The mesoderm then releases factors that induce the differentiation of the overlying neuroectoderm forming the neural plate. This stage is called the *gastrulation*. After gastrulation, the ectoderm above the notochord folds to form the neural tube, which gives rise to the brain and the spinal cord, a process known as *neurulation*. The neural folds subsequently fuse starting from the lower medulla rostrally proceeding caudally. The anterior neuropore closes at about 24 days and the posterior neuropore at 26–28 days, *primary neurulation*. The central canal is formed and is lined by ependyma. The caudal end of the neural tube formed by a group of undifferentiated cell mass develops vacuoles. These vacuoles coalesce to meet the central canal and cause elongation of the neural tube in a process called *canalization*. When caudal neuropore fails to close, open dysraphism ensues. From then until day 49 to 56, *secondary neurulation* sets in forming the conus tip and the filum terminale. Defective secondary neurulation results in the distal spinal cord connected with the epidermis by tissues of mesenchymal origin, causing tethering later on in life. The conus medullaris ascends as the spine grows, forming the caudal portion of the neural tube by *caudal regression*. From the coccygeal region during intrauterine development, the conus lies at the L2–L3 level at birth and in almost 100% by 3 months lies at L1–L2 level after full-term gestation.^{5,9,19} The spinal cord terminates at or above the inferior aspect of the L2 vertebral body in 95% of the population and at or above the L1–L2 disc space in 57% of the population. Since a defect occurs so early in pregnancy (Table 20.1), folate supplement, proven to be effective in preventing neural tube defects, has to be given in the anticipation of pregnancy.

Table 20.1: Embryological classifications of spinal dysraphism.

Developmental stage	Abnormality
Gastrulation	Neurenteric cysts and fistula Split cord malformations (diastematomyelia, diplomyelia) Neurenteric remnants Dermoid/epidermoid tumors
Canalization	Dermal sinus Pilonidal sinus Fistulas
Primary neurulation	Meningocele Myelomeningocele Myelocele Lipomyelomeningocele Lipomyeloschisis Intradural spinal lipoma
Secondary neurulation	Tight filum terminale Filum terminale lipoma
Caudal regressive	Intrasacral meningocele Sacral cysts Abnormal filum (hypertrophy, fatty infiltration)

Spinal cord anomalies result from a complex interaction between several genes and poorly understood environmental factors. Some of the risk factors that have been proposed are as follows:

1. Genetic—a family history is the strongest risk factor.^{7,18}
2. Environmental factors—folic acid deficiency; women planning pregnancy must take 0.4 mg of folic acid daily for 3 months before conception and up to 3 months during pregnancy.^{20,21} About 77% of spinal bifida cases can be prevented by this.^{7,18}
3. Medication—Some drugs taken during pregnancy can cause spinal cord anomalies. Sodium valproate and folic acid antagonist, like carbamazepine, phenytoin, phenobarbital, trimethoprim and primidone, have an increased risk.
4. Pregestational diabetes has a risk of developing both brain and spinal cord abnormalities.⁷
5. Obesity.
6. Raised body temperature.

CLINICAL EVALUATION

The clinical evaluation of a patient with a suspected spinal cord anomaly starts with a detailed history followed by clinical examination. The history should include the prenatal factors, birth history, and child's development until presentation. A prenatal history of a sibling or relative



Fig. 20.1: Hairy patch in the back of two children with underlying vertebral segmental anomalies and split cord malformation at the same level.



Fig. 20.2: Arrowhead shows a dermal sinus and the arrow shows a capillary hemangioma in a baby with underlying low-lying tethered cord with a syringomyelia.



Fig. 20.3: Excised tail of a patient presenting with a lipomyelomeningocele.

Courtesy: Mr John Firth, Nottingham, UK.

with spinal cord abnormalities and other risk factors for developing a spinal cord abnormality discussed previously should be excluded. Birth history to rule out cerebral asphyxia and trauma should be evaluated. Neurological manifestations, such as pain, altered gait, deformity, change in motor and sensory function, and bowel and bladder disturbance, should be discussed.

Physical examination starts with complete visualization of the entire body including the entire spine up to the sacral cleft. Leg length discrepancy, calf muscle thickness on both sides, inequality of feet, varus and valgus

deformities, clawing and clubfoot should be inspected. Cutaneous lesions commonly seen in spinal cord abnormalities are hairy patches (Fig. 20.1), dermal appendages, dimples, capillary hemangiomas (Fig. 20.2), nevi, subcutaneous lipomas, sinus tracts or fistula, and terminal tail (Fig. 20.3). Early scoliosis or kyphoscoliosis is an indication of possible intraspinal abnormalities. Increased frequency of urine and loss of control of bladder and bowel with other associated abnormalities discussed above may suggest intraspinal abnormalities.

Neurological examination of the central and peripheral nervous system should be performed. Delayed walking and balance in sitting or standing in a toddler should raise suspicion of a spinal dysraphism. In older children, an asymmetry of the abdominal reflexes, hyperreflexia, spasticity, mild weakness of a single limb, atrophy, painless ulceration, ataxia, altered gait, and bladder or bowel incontinence may be the only signs sometimes of an underlying intraspinal abnormality.

■ ABNORMALITIES

Lipomyeloschisis

Lipomyeloschisis is defined as a dorsal spinal dysraphism with lipoma. It consists of skin covered focal spina bifida with extension of the subcutaneous lipoma through a dural defect to the central canal of the spinal cord. This involves an extension of the lipoma into the surrounding

subarachnoid space that contains neural tissue, cerebrospinal fluid (CSF), and meninges to form a large meningocele.^{5,6,22} Tethering of the cord is very common at this level (Fig. 20.6). The bony defects that may be present involve the posterior elements of the spine, segmentation anomalies, and sacral dysgenesis. Though several forms have been described, the clinically important forms that cause progressive neurologic dysfunction via tethering are intradural lipoma, lipomyelomeningocele, and fibrolipoma of the filum terminale. Failure to differentiate the three types may lead to inaccurate prediction of prognosis.²³

Intradural Lipoma (Lipoma of the Spinal Cord)

These are fatty accumulations that are completely intradural, and often intramedullary. They are very rare comprising of 4–7% of all spinal lipomas²⁴ and 1% of all spinal cord tumors. In adults, they are found commonly in the thoracic region and tend to be dorsally located and may demonstrate an exophytic component (Figs. 20.4A to D). In children, they arise more commonly in the cervical and cervicothoracic region.^{24,25}

The pathogenesis of these tumors is poorly understood and can be associated with diastematomyelia or vertebral anomalies including spina bifida. They do not have any subcutaneous extension and symptoms are mostly due to either tethering in the lumbosacral region or due to cord compression in the cervical and thoracic region frequently becoming symptomatic in the second and third decade of life. These tumors can remain unchanged for several years but can also grow as part of the normal increase of adipose tissue that occurs throughout childhood, other than in particular conditions, such as obesity or pregnancy.²⁶ Reduction of weight in obese patients will reduce the size of the tumor and may not require surgical treatment.

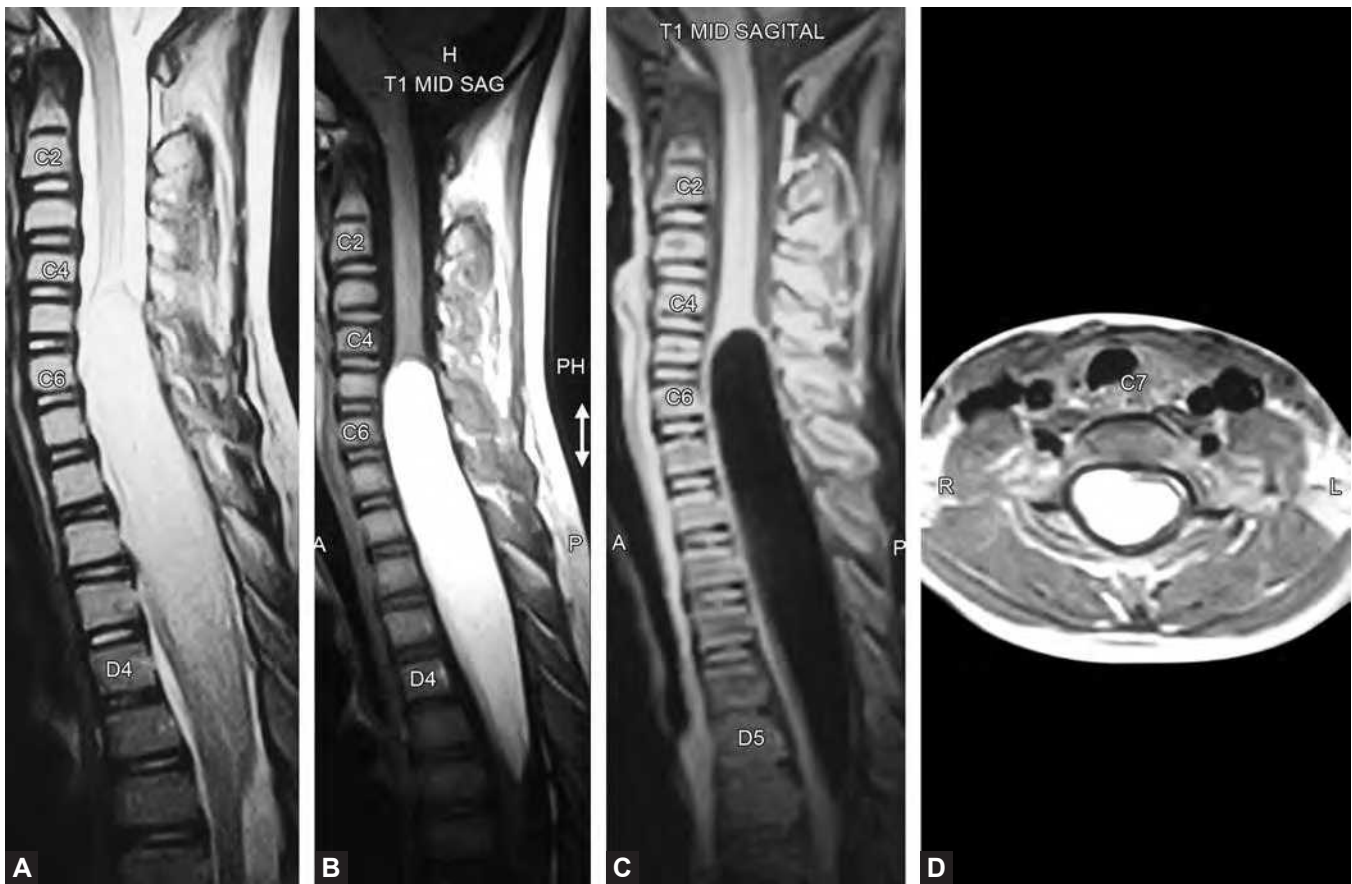
The common symptoms are pain, dysesthesia in the limbs, motor deficits, wasting, gait difficulties, and incontinence. When patients present with neurological symptoms they tend to deteriorate rapidly and surgery must be considered. The aim of surgery is to achieve tumor mass reduction as the resection margins between the tumor and the spinal cord is usually not clear (Fig. 20.5). Subtotal resection of the tumor usually gives long-lasting excellent results as they are very slow growing.

Lipomyelomeningocele or Lipoma of the Conus Medullaris

These are usually a subcutaneous fatty mass that passes through a midline defect in the lumbodorsal fascia, the vertebral neural arch, and the dura to merge and infiltrate the spinal cord causing tethering.²⁷ They occur in 1 in 4,000 births in the United States and females are more at risk.^{1,5,1,28}

Lipomyelomeningocele arise when disjunction between cutaneous ectoderm and neuroectoderm (neural tube) occur early.²⁴ The open neural tube is exposed to the ingrowth of mesodermal derivative tissues, like adipocytes (fatty mass). The adipocytes in the lumbosacral lipoma are similar to those of the normal adipose tissue except that they lie in a densely adherent fibrous connective tissue stroma. Though several terms are used in the literature to describe the lipomas in this region a classification system incorporating the anatomical features and natural history of the lipomas is used to facilitate a logical treatment approach.²⁹ This helps the surgeon to understand on the location of the neural structures, meningeal covering, and site of tethering in relation to the fatty mass. In the dorsal variant, the lipoma attaches directly to the dorsal conus medullaris and the nerve roots emerge from the ventral and lateral aspects. In the caudal variant, the lipoma from the central canal exits the cord at the filum terminale expanding the conus. The nerve roots are found to transgress the fatty mass, some of which may be nonfunctional. The final transitional variant consists of both variants and nerve roots may pass between the fatty mass and be functional (Fig. 20.7).

The diagnosis in children can often be missed unless there is a presence of cutaneous markers (50%). A nontender mass is seen in about 90% of cases usually lying in the midline. In one third of children it may be seen in a paramedian location and they present with more neurological deficits than midline masses. Asymmetrical abnormalities usually foot length, leg length, and muscle mass discrepancies are seen. Children usually presenting between 3 and 6 years of age have neurological defects at presentation compared with children who present younger.^{30,31} Bladder dysfunction presents as repeated urinary tract infections, altered or delayed voiding, or frank incontinence.²⁴ The older the child presents with urinary dysfunction the more irreversible the outcome



Figs. 20.4A to D: Magnetic resonance imaging scan of a spinal intramedullary lipoma. (A) T2-weighted (T2W) (B) T1W image of the intramedullary lipoma from C4 to D6, (C) fat suppression of the tumor and (D) axial T1W image showing the tumor expanding the entire spinal canal with a thin rim of cord at the anterior later edge.

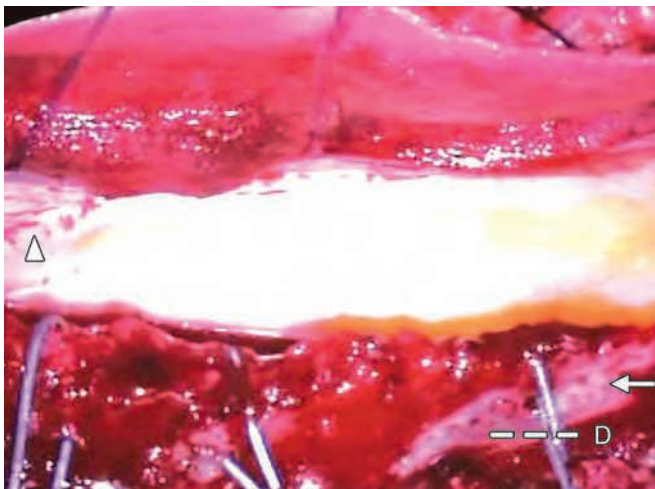


Fig. 20.5: Microscopic view of intramedullary spinal lipoma showing the cord at the cranial end (arrowhead) expanding into the tumor and the open door laminoplasty edges held by Ethibond (arrow) sutures.

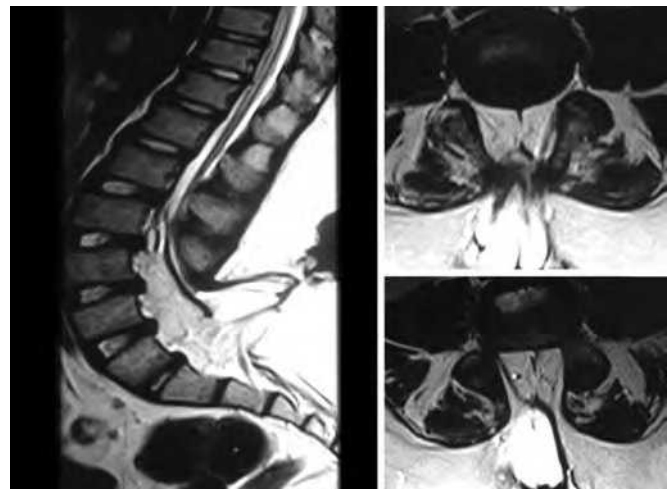


Fig. 20.6: The magnetic resonance imaging scan shows a lipomyelomeningocele with spina bifida and tethered filum.

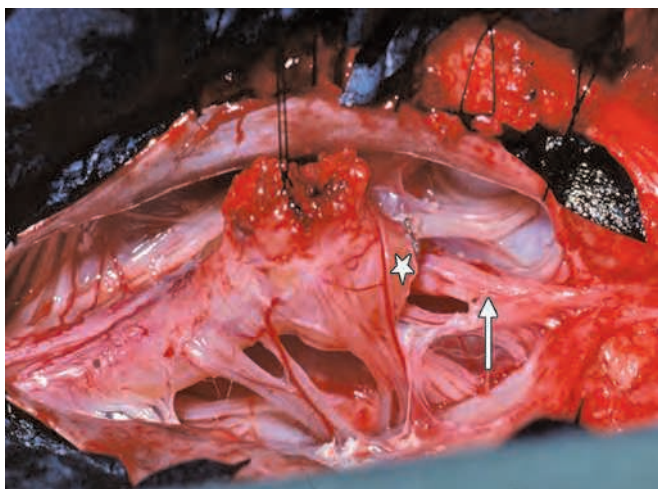


Fig. 20.7: Operative picture shows a low cord at S3 level, a split cord and double film (arrow) lying in the anteroposterior plane and a closed lipomyelomeningocele of a transitional variant (star). *Courtesy: Mr John Firth, Nottingham, UK.*



Fig. 20.8: T1-weighted magnetic resonance imaging of the lumbosacral spine in a patient presenting with back pain showing an hyperintense elongation of the fatty filum with the cord lying at L1 level.

even with surgery. Adults usually present with back pain or neurological deficits including bladder symptoms. Pain is generalized or radicular and can be precipitated by physical activity or trauma. The clinical features are usually due to the tethering effect produced by the lipomyelomeningocele and may be either due to the direct mechanical tension causing neurological deficits³² or due to ischemic injury from tethering.^{32,33}

In patients presenting with clinical deficits the decision is straightforward. In those who do not have a detectable neurological symptom or deficit there is no consensus regarding prophylactic surgery. Though prophylactic surgery for asymptomatic congenital spinal lipomas remains controversial there is growing evidence in favor of surgery, which offers longer progression free survival. The argument offered against prophylactic surgery is that it does not prevent late neurological deficits irrespective of surgery intervention.³¹ The goals of surgery are to release the tethering and reduce the bulk of fatty tumor. Surgical treatment after neurological deterioration has poor unacceptable outcomes. With better understanding of the anatomy of spinal lipomas and advanced microneurosurgical techniques, surgery is safer and prevents long-term outcome. In children born with a lipomyelomeningocele mass surgical treatment is indicated when the patient reaches 2 months of age. Overall, with surgery, 19% will improve, 75% will be unchanged, and 6% will worsen, and foot deformities often progress regardless. The risks involved in surgery are also higher include CSF leak and infection

being as high as 10–20%, neurological deterioration from 2% to 7%,^{34–36} and retethering and late deterioration.³⁴

Fatty Filum or Lipoma of the Filum Terminale

This is defined as an accumulation of fat within the terminal filum with an incidence of 13–26%.³⁷ Radiologically, it is seen as a thickening of the filum >2 mm with fat deposition demonstrated on T1-weighted magnetic resonance imaging (MRI) (Fig. 20.8). The thickened filum can resist ascent of the conus medullaris causing tethering and occasionally contribute to neurological deterioration.

They usually form part of occult dysraphism with no cutaneous markers. They can occur alone or as part of a caudal regression syndrome during secondary neurulation, with involvement of cloacal and urogenital structures.^{38,39} They are usually asymptomatic until the adolescent growth spurt.

Back pain is the commonest symptom often exacerbated by stretching, physical activity, and trauma. These lesions are being commonly recognized after the routine use of MRI scans and the natural history is still not clear. Hence, the surgical management of fatty filum is debatable given the poor understanding of the natural history. The management is based on the presence of pain or neurological signs and the position of conus medullaris. When the filum is thick and the patient is symptomatic with low-lying conus the management is surgical division. Controversy, however, arises when the patient has

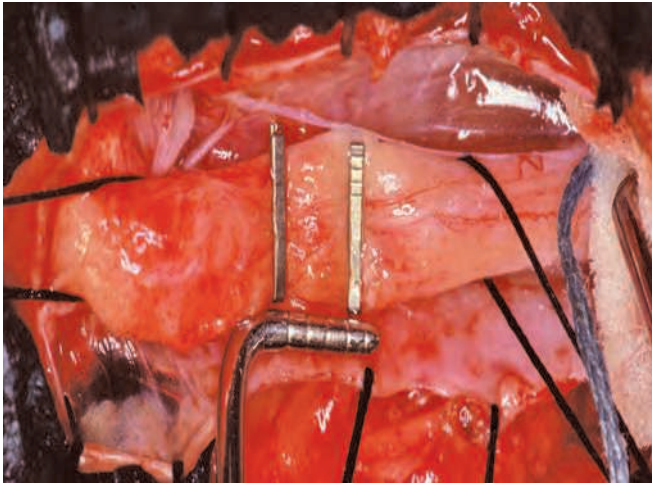


Fig. 20.9: Division of the thickened film terminable infiltrated with fat.
Courtesy: Mr John Firth, Nottingham, UK.

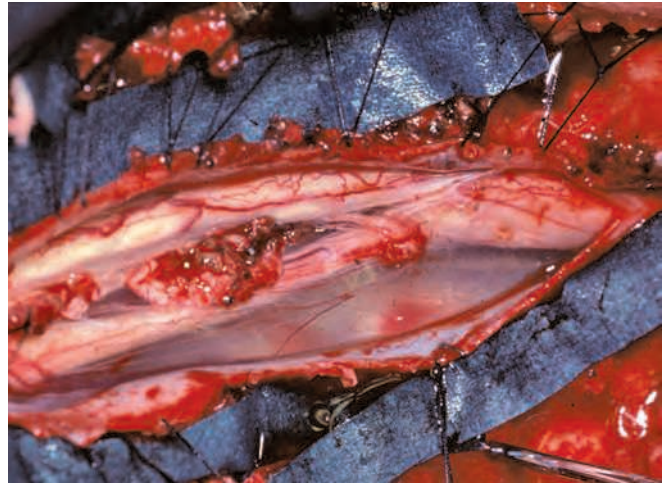


Fig. 20.10: Split cord malformation shows two cords, multiple midline "pegs", which represent duplicated dural tubes, pedicles and laminae. Medial nerve roots are seen.
Courtesy: Mr John Firth, Nottingham, UK.

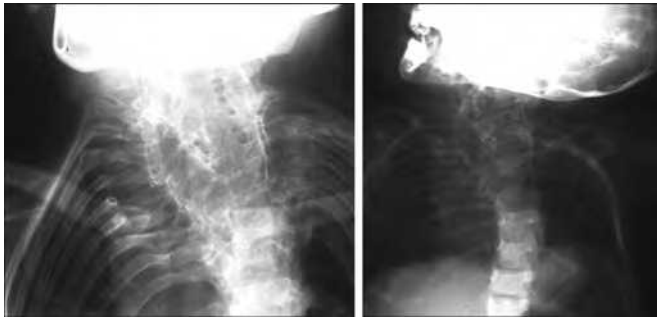


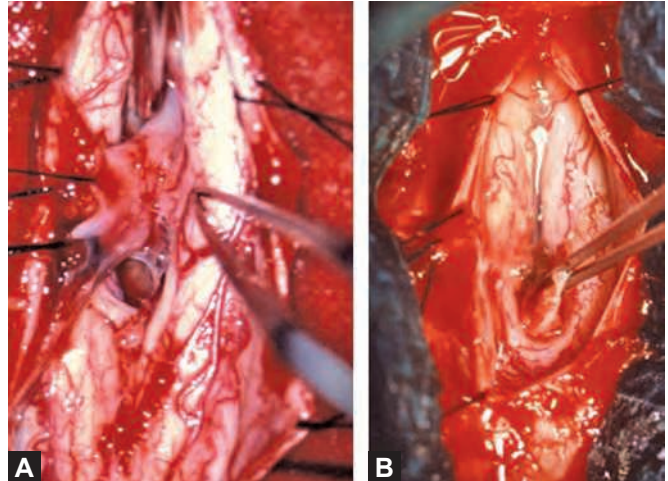
Fig. 20.11: X-ray of the cervicothoracic junction showing duplicated canals and duplicated neural arches with two pairs of pedicles at each level.

low-lying conus with no symptoms or a normal position of conus with symptoms of tethering. Given the low complication rate with this procedure, surgery is a reasonable option in this situation after a detailed discussion about the risk and outcome of the procedure with the patient (Fig. 20.9).

SPLIT CORD MALFORMATION

Split cord malformation (SCM) is an anomaly where the spinal cord is split over a portion of its length to form a double neural tube. The two hemicords may be contained within a single dural sheath, or each may be contained within its own separate dural sheath. Both have a common embryonic origin.

Type I SCM, otherwise commonly referred to as diastematomyelia, is defined as two hemicords, each with its



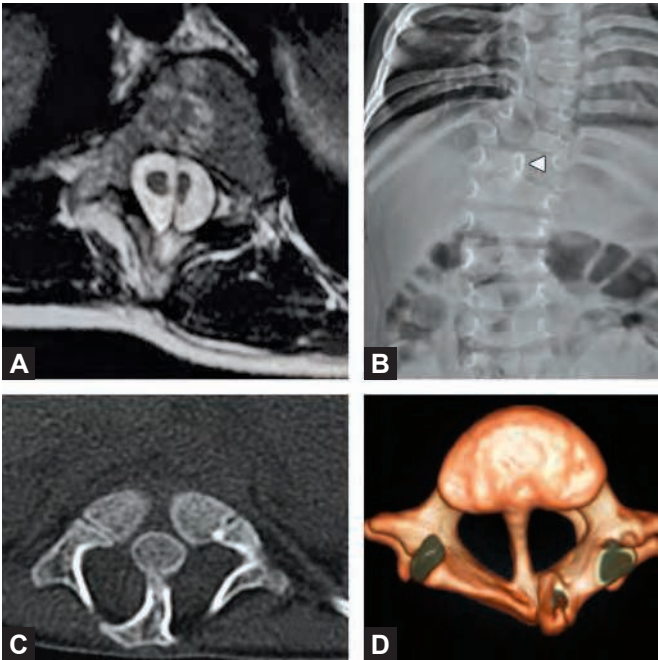
Figs. 20.12A and B: (A) Short split with a membranous peg clear of reuniting cords. The roots are seen medially. (B) Short and tight split cord malformation seen with traction of the cord with a higher auxiliary bony peg.

Courtesy: Mr John Firth, Nottingham, UK.

own central canal, lying within separate dural tubes, which are separated by fibrous (Fig. 20.10), or osseocartilaginous (bony) median septum. They have a single set of dorsal and ventral nerve roots (Figs. 20.13A to D). They may also present with duplicate spinal canals, duplicated neural arches with two pairs of pedicles at each level (Fig. 20.11). Other abnormalities of the spine at the level of the split are an absent disc and a dorsal hypertrophic bone where the median bony spike lies (Figs. 20.12A and B). Two-thirds of type I SCMs have overlying skin abnormalities and are

Table 20.2: Differences between the two types of split cord malformations.

Type 1: <i>Diastematomyelia</i>	Type 2: <i>Diplomyelia</i>
Cord split into two half with its own dural sheath	Cord split into two half within one dural sheath
Single lateral set of dorsal and ventral roots	Medial and lateral sets of dorsal and ventral roots
Midline bony, cartilaginous or fibrous tethering bands present	Usually none present
Associated with Spina Bifida, cutaneous markers, hydromyelia, Klippel–Feil syndrome, hydrocephalus, Arnold–Chiari malformation and intradural teratomas	Also associated with the same



Figs. 20.13A to D: (A) Magnetic resonance imaging axial T2-weighted image shows a fibrous septum with split cords, (B) computed tomography (CT) scan shows a bony peg growth in the spinal canal (arrowhead), (C) Anteroposterior X-ray view shows a midline bony spur and (D) three-dimensional CT reconstruction shows the bony peg in the axial view.

associated with spina bifida, Klippel–Feil syndrome, Chiari malformation (CM) and intradural lipomas, and teratomas.

Type II SCM, referred to as diplomyelia, is defined as two hemicords within a single dural tube, separated by a nonrigid fibrous median septum. They usually have a dorsal and a ventral nerve roots arising from each hemicord. There is usually no spine abnormality at the level of the split, but there can be an associated spina bifida.^{5,40,41} Dystrophic median nerve roots projecting from one or both hemicords have been associated with both diastematomyelia and diplomyelia. The difference is summarized in Table 20.2.



Fig. 20.14: Split cord malformation with neurenteric remnants including the gut, fatty tissue and also liver.
Courtesy: Mr John Firth, Nottingham, UK .

Split cord malformations are usually located in the lumbar and the thoracic regions and are more common in girls^{6,42} with type I being more frequent than type II.⁴³ They typically produce neurological deficits after 43 months of age.⁴³ Spina bifida occulta can present in 50–80%. Midline thoracic or lumbar cutaneous abnormalities are common.

Various theories have been proposed for the development of SCM. Several theories hold good to explain a variety of midline anomalies composed of tissues derived from any of the three primary germ cell layers. During the notochordal split the remnants of the endodermal-ectodermal adhesion could give rise to endodermal remnants anywhere between the gut and the cutaneous ectoderm (Fig. 20.14). Visceral malformations are exceedingly common when the enteric contents are seen. If the neurenteric tract persists further dorsally to involve the ectoderm, an associated myelomeningocele can occur.

The most frequently occurring lesion is a hairy patch in 40–50% and others include lipomas, dimples, hemangiomas,

sinus tracts and fistulas, and meningocele or myelomeningocele. The level of the cutaneous skin lesion does not correspond to the level of the SCM. Spine deformity is more likely to occur with higher lesions and, when present, increases with age. The deformity is predominantly due to presence of hemivertebrae and spine bifida. The cord may be asymmetrically split with one leg shorter or underdeveloped with the corresponding thinner cord (Fig. 20.15). Similarly a syringomyelia when present usually is seen higher to the split and may occasionally extend into one of the hemicords. In 85% patients at least one lesion causing a spinal tether will be found with the cones lying below L2. The causes of tether include a thick film, fatty film, lipoma, dermal sinus tract, or a myelomeningocele.⁴⁴ A thickened film followed by a myelomeningocele is the commonest cause.

If a patient is asymptomatic, SCM does not require any treatment. When a patient is symptomatic from cord traction and dysfunction from a bony peg and tethering surgical resection of the bony spur followed by detethering of the film is required. If there is no bony peg then only detethering will be required. Most patients present with tethering of the cord and symptoms improve with untethering.⁴⁴ The other situation that is commonly encountered is a SCM in association with a vertebral deformity, which requires correction. In this situation the bony spur removal and detethering is performed as a primary procedure followed by a deformity correction 3–6 months later. Spinal cord monitoring can be used during the procedure. There is currently no literature to support performing both surgeries in the same setting.

DERMAL SINUS, DERMOID, AND EPIDERMOID CYSTS

Dermal sinus is defined as an epithelium lined fistula extending from the skin surface and can connect with the dura as well as the spinal cord. The sinus tract may terminate in the subcutaneous tissue, bone, dura, subarachnoid space, or film terminale. It may pass between normal vertebrae or through a bifid spine to attach to the dura. Infrequently, this can cause tethering of the cord.^{6,26} They result from a failure of the surface ectoderm and the dermal elements to separate from the neuroectoderm. They may appear as a dimple or a small sinus opening measuring about 1–2 mm in diameter. It can present with hair in the midline or paramedian and the surrounding skin may appear normal or pigmented “port wine stain.” Dermal

sinus tract may terminate in a dermoid or epidermoid cyst and can directly communicate with the dura as well as spinal cord in 11.3% of cases.⁴ This can cause either spinal cord or cauda equina compression or tethering effect.

A dermoid cyst is lined with dermis (skin appendages—hair follicles, sebaceous glands) and secretes sebum, while an epidermoid cyst is lined with stratified squamous epithelium containing keratin and cholesterol from desquamated epithelium. As a result this can predispose the contents of the tract to cause irritation and spread to the dura and cause chemical or infective meningitis (*usually Staphylococcus aureus*) that can be recurrent and less frequently intrathecal abscess and arachnoiditis. Less serious, local infections can occur. It is found more frequently in the lumbosacral region, although cervical, thoracic, and occipital locations are possible.^{4,5} They may connect to a fatty film, a low-lying conus medullaris, or an intraspinal lipoma. Pilonidal cysts are a different entity, which may also be congenital containing hair, are located superficial to the post sacral fascia, and may become infected.

When examining a baby for possible spinal dysraphism the natal cleft must be separated and examined for a small sinus or dimple hidden underneath. The incidence in neonates is approximately 1–2%, but the true incidence may be unknown. Dermal sinus tracts that are found above the natal cleft are usually directed superiorly (Fig. 20.16). Coccygeal pits or dimples are found within the natal cleft with a tract extend either straight down or inferiorly below the subarachnoid space. These may not need to be treatment unless they develop any signs of infection. Although these are seen at birth occasionally patients are not referred to medical attention until they develop an infection or meningitis as their first presentation. When seen at birth an ultrasound can be performed to look for a spina bifida or mass lesion intradurally. Magnetic resonance imaging best shows the underlying abnormalities and can track the sinus and its attachments. The previously proposed injection with contrast into the sinus should be avoided to precipitate infection.

Dermal sinuses above the gluteal crease should be surgically removed. Treatment of more caudally located sinuses is slightly controversial. Although approximately 25% sacral sinuses seen at birth will regress to a deep dimple it is recommended that the tract should be followed intradurally and the associated dermoid lesion should be excised (Fig. 20.17). There is no justification for a conservative approach as such a therapy risks the development of meningitis.

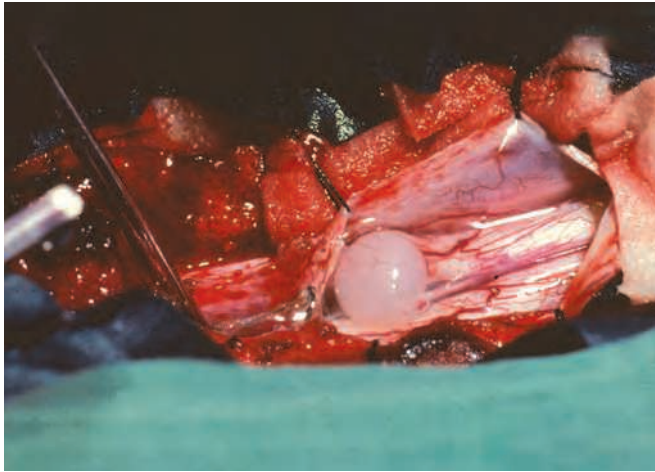


Fig. 20.15: Split cord malformation with one hemicord thinner than the other and the neurenteric remnant seen here is the lung. *Courtesy: Mr John Firth, Nottingham, UK.*



Fig. 20.16: A congenital dermal sinus above the natal cleft.

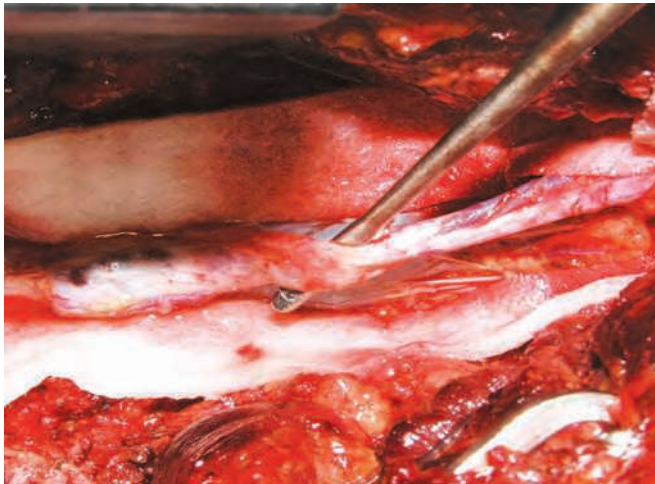


Fig. 20.17: Operative picture showing the sinus tract held with a retractor close to the dural attachment.

SACRAL AGENESIS AND CAUDAL REGERSSION SYNDROME

The filum terminale and the cauda equina are formed from the caudal part of the neural tube by regression. During the formation of the primitive streak the caudal end of the embryo forms a caudal eminence. This separates itself from neural tube and forms the film terminale, cauda, and conus medullaris by retrogressive differentiation. Failure of retrogressive differentiation may also give rise to lipomas and myelocystoceles. During this process, a localized dilation of the central canal, the ventriculus terminals,

arises in the cones. The caudal eminence also gives rise to the other structures including the anorectal canal (distal colon, rectum, and anus) and urogenital sinus (bladder, urethra, and genitalia). The cloacal membrane eventually ruptures to become a perforate anus. Cloacal folds ultimately differentiate into male or female genitalia. The conus medullaris initially rests in the coccygeal region and ascends with life to lie at the L2–L3 at birth and reaches its destination at the L1–L2 level by 3 months. Gestational diabetes plays a role in the embryogenesis of these malformations is particular.

Simple agenesis of the sacral and the coccyx to serious anomalies of the caudal spine involving the sacral spine, lower extremities, spinal cord (Fig. 20.19), genitourinary system and gastrointestinal tract have been described. Sacral agenesis is suspected by flattening of the buttocks, shortening of the intergluteal cleft, and prominent iliac crests. Based on the radiological appearance of sacrum, Pang classified sacral agenesis into five types. Abnormalities in the foot are suggestive of vertebral segmentation anomalies.

Sometimes a baby is born with significant and serious defects including omphalocele, cloacal artesian, cardiac problems, genitourinary problems, and tracheoesophageal fistula. They may require immediate operation and then followed by more detailed MR evaluation to look for spinal abnormalities. Tethering is a common finding (Figs. 20.18A and B) in 24% of children with anorectal malformations and in 43% of children with complex malformations. Myelocystocele or lipomyelomeningocele with tethered spinal cord present with a soft fatty mass in the lumbo-sacral region. Surgery for tethering should be performed



Figs. 20.18A and B: T2-weighted (T2W) magnetic resonance imaging (MRI) (A) and T1W MRI (B) showing sacral agenesis and caudal regression with a tethered and low-lying cord.

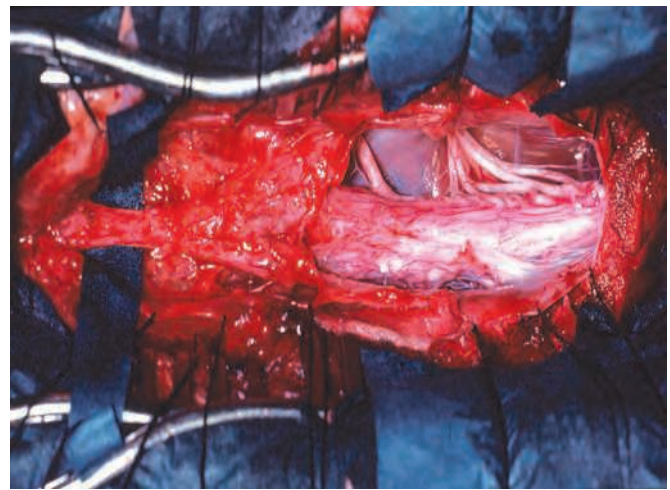


Fig. 20.19: Spinal cord extending below the arachnoid reflection seen in caudal regression syndrome.

Courtesy: Mr John Firth, Nottingham, UK.

after improving the general condition of the child. Early untethering is associated with improvement in motor and sensory preservation and improvement.

SYRINGOMYELIA AND CHIARI MALFORMATION

Chiari Malformation

Chiari malformation (CM) is a malformation of the posterior fossa of the brain. It consists of a downward displacement of the cerebellar tonsils through the foramen magnum (FM). The displacement is generally about 5 mm or more. The true incidence of this malformation is unknown. In a study of the 22,591 patients who underwent MRI of head, 175 (0.775%) were found to have tonsillar herniation extending >5 mm below the FM.⁴⁵ Various authors have reported a familial incidence ranging from 3% to 12%.^{46,47}

The development of the deformity has a genetic basis. This is supported by the presence of a familial incidence. However, the exact cause for this deformity has not been clearly elucidated. Various theories have been postulated to explain the development of features seen in CM. Williams⁴⁸ suggested that the pathogenesis is due to the differential cranial-spinal pressure gradient across the FM. This led to an altered CSF circulation at the FM, which prevented instantaneous pressure equilibration between the intracranial and the spinal subarachnoid space. This results in development of an intermittent vector force,

which, with each Valsalva maneuver, leads to the progressive downward movement of developing tissue through the FM. This craniospinal dissociation most accurately accounts for most of the features associated with the CM and also explains the basis of the current form of proposed treatment, i.e. posterior fossa decompression.^{48,49} Schady et al.⁵⁰ found that the posterior fossa volume was 23% smaller in patients with CM I than in controls thus suggesting that the herniation occurred due to the mismatch between the rapid growth of the brain during the first year with a small developmental posterior cranial fossa.

Types of Chiari Malformations

Hans Chiari, an Austrian pathologist, was the first to describe this entity in 1896, following postmortem examinations. He initially described Chiari types I, II, and III; he later added type IV. Chiari type I, is characterized by a displacement of the cerebellar tonsils 5 mm below the FM or at C1 level and rarely below C2–C3. Hydrocephalus is reported in 3–10% of the patients with Chiari type I malformation. A more frequent observation is syringomyelia, reported in 50–75% of cases (Fig. 20.20). Syrnix cavities are usually found in the cervicothoracic spinal cord. Approximately 50% of Chiari I present with basilar and craniovertebral anomalies, the most common being basilar invagination and occipitalized Atlas. Abnormalities of the fourth occipital sclerotome appear to be closely related to hindbrain malformation, which are often seen



Fig. 20.20: Chiari malformation with tonsils at below the C1 posterior arch with a syringomyelia.

in conjunction with CM. Other commonly seen osseous lesions include platybasia, atlantoaxial dislocations, and Klippel–Feil anomaly. In CM II the displacement not only includes the cerebellar tonsils, but also the vermis, fourth ventricle and lower brain stem below the level of FM. Almost all cases of myelomeningocele present with Chiari II, though the reverse is not true all the time. Hydrocephalus is seen in 90% of the cases and ventricles are seen asymmetrical. The fourth ventricle is small and deformed. Syringomyelia and bony abnormalities in the upper cervical spine shows Klippel–Feil anomaly with hypoplastic posterior arch of C1. Chiari malformation III remains as a rarely identified entity, which includes all of the characteristics found in CM I and II and also includes a herniation of cerebellum in a occipitocervical encephalocele.⁵⁷ Chiari malformation IV is characterized by marked cerebellar hypoplasia or aphasia and tentorial hypoplasia. There is no hindbrain hernia ion. It is very rare and is noncompatible with life.

Recently more “Complex Chiari” malformations have been defined as with radiographic findings of brainstem herniation through the FM, medullar kink, retroflexed odontoid, abnormal clival–cervical angle, occipitalization of the atlas, and basilar invagination. Detailed evaluations using current imaging methods have introduced more subtle forms of the malformation currently named as Chiari 0 and Chiari 1.5 and have also introduced terms like “asymptomatic” and “incidental” CM depending upon the extent of cerebellar ectopia and clinical findings. In Chiari 0 there is minimal or no hindbrain herniation

and syringomyelia. Many of them show cranial–cervical abnormalities of type I and at surgery reveal arachnoids adhesions and bands with a crowded FM. A more recent entity of Chiari 1.5 has been described, and it specifically concerns with patients with tonsillar herniation but without brainstem elongation or fourth ventricle deformation.

Clinical Presentation

The clinical presentation with CM I in early childhood differs from the clinical features observed in the adult patient population. Children younger than 3 years present with oropharyngeal dysfunction, such as aspiration, regurgitation, choking, dysphagia and abnormal vocal cord function. Chronic cough is thought to be the major presentation in children younger than 3 years of age. While older children present with headache and scoliosis. Park et al.⁵⁸ found pain to be the most common feature in (63%), numbness (26%), motor weakness (19%), and in-coordination (16%). In the older group of adolescents, 91% presented with pain, 27% had scoliosis. In a large series of adult patients, 81% presented with suboccipital headache, distinctively worsening on physical exertion and Valsalva maneuvers, head dependency, and posture changes.⁴⁵ Patients with CM II almost all cases present with myelomeningocele. The common presentation features consist of lower cranial nerve deficits, cerebellar dysfunction, and respiratory difficulty. With increasing severity in Chiari II respiratory insufficiency and apnea contribute to mortality. Progressive tethering and/or formation of syrinx usually starting from the site of myelomeningocele repair produce progressive neurological deficits in this group. Chiari III malformations are the rarest form of hindbrain deformities characterized by occipital and/or cervical encephalocele. These children present with severe neurologic deficits including delayed milestones, seizures, ataxia, spasticity, and other features common to Types I and II. They are rare and fatal in early infancy.

Treatment of Chiari Malformation

Periodic neurologic examinations with imaging evaluations are favored for asymptomatic Chiari I, especially, when the syrinx is <2 mm. Surgical intervention is favored for the symptomatic cases. The current practice involves suboccipital bony decompression including FM and C1 posterior arch, followed by opening of the durra with

release of all arachnoid adhesions and augmentation with duraplasty to facilitate CSF circulation around the cranio vertebral region. In all cases, the thickened arachnoid membrane bridging the cerebellar tonsils are released, and the cerebellar tonsils are coagulated to shrink the size and improve the volume of posterior cranial fossa. The fourth ventricle is visualized by gentle dissection and any adhesions released. The treatment for Chiari type II includes repair of the myelomeningocele and treatment of hydrocephalus by placing a shunt tube. The changes due to brainstem deformity do not show improvements with surgical correction or shunting of hydrocephalus and thus tend to produce progressive neurological worsening. Periodic evaluations for brainstem malfunction need to be performed, especially for respiratory function, swallowing and speech. If progressive brainstem compression is clinically evident, posterior fossa decompression is indicated in such cases.

Syringomyelia

It is a term applied to a progressive disorder of the spinal cord characterized by cavitations in its substance, presenting clinically as a syndrome of lower motor neuron signs in upper limb, upper motor neuron signs in lower limb, and segmental dissociative sensory loss. In syringomyelia, cavitations outside the central canal are seen and it is not lined by ependyma. Syringomyelia can either be communicating with the fourth ventricle and the central canal as seen in CM and basilar arachnoiditis or noncommunicating as in spinal cord tumor, spinal cord trauma, and spinal arachnoiditis.

Based on the etiology, Barnett's classified syringomyelia as follows:

- Associated with congenital anomalies of the FM and posterior fosse (Chiari syndrome, dandy walker syndrome and basilar invagination).
- Associated with acquired basal abnormalities, such as basal arachnoiditis, posterior fossa tumors.
- Post-traumatic.
- Associated with spinal tumors.
- Idiopathic.

Clinical Presentation

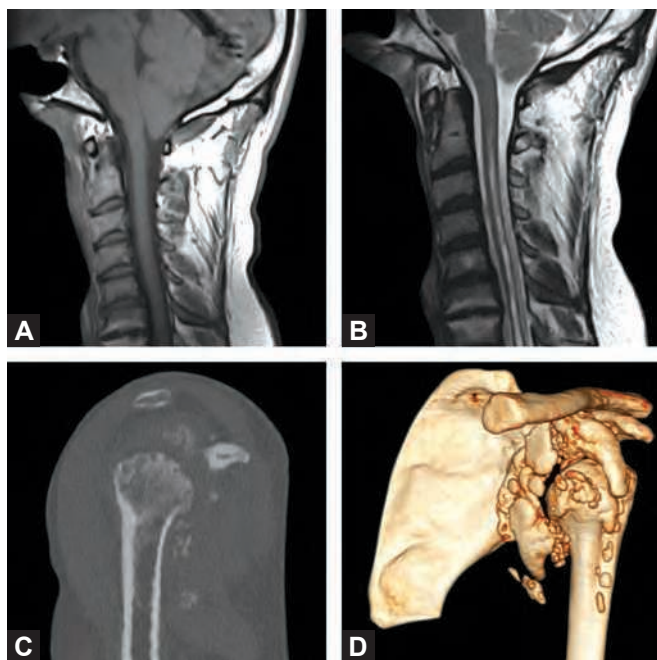
It is commonly present in the second and the third decade. In early stages, complaints include pain in the cervical region and occipital region related to coughing and sneezing, numbness in the upper limbs and trunk

associated with weakness in the upper limbs and difficulty in walking due to myelopathy. Syrinx may extend into the medulla, producing a syringobulbia characterized by dysphagia, nystagmus, vertigo, tinnitus, deafness, pharyngeal and palatal weakness, asymmetric weakness and atrophy of the tongue, and sensory loss involving primarily pain, and temperature senses in the distribution of the trigeminal nerve. Dysesthetic pain, which can be very troublesome usually, involves the neck and shoulders, but may follow a radicular distribution in the arms or trunk.

Signs include structural features, such as scoliosis, hemiatrophy, asymmetry of the face and upper limbs. Patients may have features of spinal dysraphisms. Charcot's joints due to sensory deficits are commonly seen in the upper limb. Klippel-Feil deformity with features of decreased neck movements, low hairline, and short neck may be evident. The expanding cavity disrupts the decussating spinothalamic fibers that mediate pain and temperature sensibility, resulting in loss of these sensations, while light touch, vibration, and position senses are preserved. This may be lost in one or both arms. As the cavity enlarges further it involves the posterior columns with loss of position and vibration senses in the feet, astereognosis may be noted in the hands. When the extension is into the anterior horns it damages motor neurons causing diffuse muscle atrophy that begins in the hands and progresses proximally to the shoulder girdles. Claw hand may develop in late stages. Painless ulcers of the hands and sometimes the foot are frequent. Neuropathic joints (Charcot joints) may affect the shoulder, elbow, or wrist.⁵⁹ Scoliosis is seen sometimes.⁶⁰ Acute painful enlargement of the shoulder is associated with destruction of the head of the humerus as in Figures 20.21A to D.

Scoliosis Associated with Chiari Malformations and Syringomyelia

Scoliosis is the most common musculoskeletal deformity seen in cases of Syringomyelia and Arnold-Chiari malformations. The postulated mechanisms for development of the spinal deformity have not been clearly elucidated, although several theories have been proposed. Some authors have suggested the idea of an asymmetrically enlarging cyst that injures either the lower motor neurons or the dorsomedial and the ventromedial nuclei of the gray matter of the anterior horn of the spinal cord, thereby creating imbalance of trunk musculature and predisposing to scoliosis.^{51,52} Gardner et al.⁵³ suggested



Figs. 20.21A to D: Patient with Type 1 Chiari malformation and a neuropathic left shoulder. (A) T1 weighted (T1W) MRI shows tonsils at the level of C1. (B) T2 weighted (T2W) MRI shows a thin syrinx extending below cervical spine. (C) X-ray of shoulder showing destruction of the humeral head. (D) 3-D reconstruction showing a Charcot's shoulder.

that during fetal development, the mass effect of the syrinx caused vertebral deformity, resulting in scoliosis. Thus, the lack of understanding of the pathophysiology of scoliosis in syringomyelia makes it difficult to determine the effect of syrinx on the natural history of the spinal curve.

Scoliosis associated with syringomyelia has been noted with several findings, including young age of presentation, atypical curve, rapid curve progression, and back pain. The presence of a syrinx complicates the treatment of scoliosis, because spinal distraction and instrumentation have been associated with an increased risk for neurologic deficits.

Predictors of Curve Progression

The natural history of scoliosis in syringomyelia and CM has not been clearly defined. Flynn et al.⁵⁴ in a 15-year retrospective institutional review concluded that progression of spinal deformity after neurosurgical management of Chiari I malformation was associated with age >8 years at neurosurgical decompressions and initial neurologic symptoms, double scoliosis curve patterns, kyphosis, rotation, rigid curves, and larger curve at presentation. Chiari

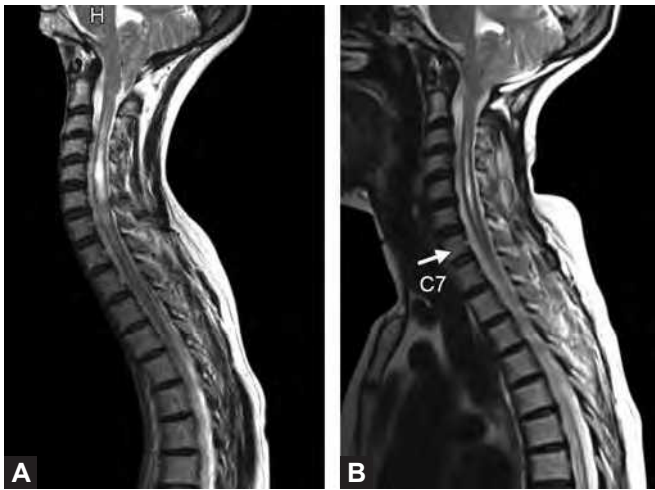
malformation and syringomyelia benefit from suboccipital craniectomy prior to deformity correction surgery. It gives best chance for syrinx reduction and scoliosis improvement, particularly in children younger than 10 years.⁵⁵ Syrinx shunting surgeries do not afford any benefit, as they do not improve the scoliosis. Cases with congenital scoliosis or myelomeningocele, neither stand to benefit from the neurosurgical procedure since the cause of the curve remains untreated.⁵⁵ Krieger et al.⁵⁶ in review of 79 cases concluded that patients who presented with scoliosis and were found to have a CM I with a syrinx, a CM I decompression alone was adequate treatment for mild scoliosis of <20°. For patients with curves greater than 25°, the risk of curve progression is high even after a CM I decompression and syrinx resolution, with 70% (21 of 30 patients) in this subgroup requiring further orthopedic treatment of bracing or surgery. Age greater than 10 years generally is associated with curve progression irrespective of suboccipital decompression.

Resolution of Syringomyelia

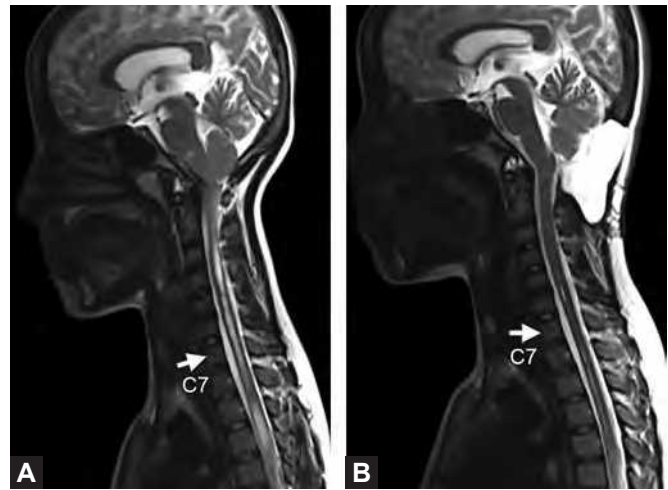
Syringomyelia is seen in >80% of patients with CM. The effects of suboccipital decompression on resolution of syringomyelia are more consistent as compared to the effect on scoliosis. The efficacy of CM I decompression in terms of syrinx resolution, neurological improvement was demonstrated by Kreiger et al.⁵⁶ with MRI studies. They demonstrated resolution of the syrinx 6 months postoperatively in 87% of the patients, resolution of the neurological findings was seen in 80% of the patients and 69% had resolution of headache symptoms after suboccipital decompression. We have shown two patients with resolution of syrinx following suboccipital decompression (Figs. 20.22 and 20.23).

TETHERED CORD SYNDROME

Tethered cord syndrome (TCS) is been defined as a spectrum of congenital anomalies resulting in an abnormally low position of the conus medullaris, usually lower than the L2 vertebra or below the L1-L2 disc space,⁶¹ that may lead to neurological, musculoskeletal, urological, or gastrointestinal abnormalities. Classically, the film terminable is thickened with low-lying cones whose symptoms improved following detethering. Currently, a more accepted diagnosis of TCS is defined as a pathological fixation of the spinal cord in an abnormally lying position.⁶¹ Most recently, TCS has been described to have the cones at a



Figs. 20.22A and B: Pre- (A) and postoperative (B) picture of a type I Chiari malformation with syringomyelia shows good resolution of the syrinx cavity following foramen magnum decompression.



Figs. 20.23A and B: Pre- (A) and postoperative (B) picture of a type I Chiari malformation with syringomyelia shows good resolution of the syrinx cavity following foramen magnum decompression. Postoperative pseudomeningocele is seen.

normal position on imaging but with signs and symptoms consistent with TCS. They have associated findings such as cutaneous stigmata, vertebral abnormalities, intradural lipoma and neurological abnormalities on examination. Among these patients, symptoms of pain and bowel or bladder incontinence appeared to be responsive to detethering.

During development distal to the posterior neuropore, undifferentiated cells from the primitive streak form the caudal cell mass that develops into the conus medullaris, cauda equina, and film terminale. During the end of the canalization period (days 43–48), the ventriculus terminalis forms at the terminal end of the neural tube near the coccyx.⁶² Neural tissue caudal to the ventriculus terminalis undergoes retrogressive differentiation to form the film terminale and cauda equina. Simultaneously, the vertebral column grows at a disproportionate rate to the spinal cord, resulting in the ascension of the cones and elongation of the filum. The cauda equina forms, as nerve roots grow longer to accommodate the differential growth. The regression process continues into the postnatal period with the cones reaching the adult level of L1–L2 by approximately 3 months of age.

The pathophysiology of TCS involves the existence of traction and the loss of the elasticity of the filum terminale as well as ischemic insult to the cord. The extension of the spinal cord, the metabolic abnormalities observed, and the decrease in spinal cord blood flow leads to neurological

deficits.^{63,64} Tethered cord syndrome can either be primary when associated with congenital abnormalities of the cord or secondary tethering following intradural surgery for congenital abnormalities or tumors.

Clinical Presentation

Toddlers and Young Children

Back and lower extremity pain may be a presenting complaint in this age group, associated with both motor and sensory dysfunction. Delay in developmental milestones in toddlers, while gait difficulties, bladder disturbances, sensory deficits, development or progression of scoliosis, or foot deformities in older children may reveal clues to TCS. Sensory loss tends to occur in a nonsegmental distribution.

Older Children and Teenage

Nondermatomal pain in the lumbosacral region, perineum, and legs with activity is the predominant symptom. Progression of a scoliosis deformity often contributes significantly to complaints of pain. Urinary incontinence may also be a predominant symptom.

Adults

With a known history of spina bifida, the clinical presentation is similar to that in adolescents with exacerbation of

pain and sphincter dysfunction related to activity. Weakness may be subtle and present only in a single muscle group. In adults who present without a previous history of spina bifida, pain is the most common presentation followed by weakness, unsteady gait, and urological dysfunction. A history of sexual dysfunction may be the only presentation with TCS in adults. Other uncommon presentations are chronic fatigue, perineal pain, patchy sensory loss including the sacrum and recurrent bladder infections. In the patients without orthopedic deformities or urological dysfunction, trauma often leads to new onset of symptoms. The trauma may be mild (child birth, exercise) or involve a major direct trauma to the spine. Trauma increases the stress on the already tense spinal cord, altering microcirculation and cellular metabolism and eventually leading to neurological deterioration.

Examination

Newborns and children with TCS may have cutaneous markers suggesting investigation for underlying problems. The frequently seen cutaneous markers are myelomeningocele sac, cutaneous hemangioma, hypertrichosis, subcutaneous lipoma, dimple and dermal sinus, and pigmented nevus. Patients often have more than one symptom or sign (Fig. 20.25). However, one of the clinical features is usually predominant over the other. Some of the common clinical signs are weakness of the lower limbs, absent reflexes, muscle atrophy followed by spasticity, and contractures in extreme cases, patchy sensory loss, bowel and bladder dysfunction, and rarely tropic painless ulcers in ankle and foot.

Diagnosis

Magnetic resonance imaging is the radiographic modality of choice for evaluating TCS. Magnetic resonance imaging demonstrates the level of the conus, often visualizes the cause of tethering, and provides detail for potential surgical planning (Figs. 20.26A to C). Common lesions seen on MRI associated with TCS, including meningoceles, and myelomeningoceles, SCMs, dermal and lipomatous tumors, are all readily demonstrated on MRI. Thickness of the film terminale greater than 2 mm is considered abnormal in children. Urodynamic studies are useful in assessing the bladder capacity, pressure, electromyogram activity, and sphincter function. Detrusor hyper-reflexia,

reduced bladder compliance, dyssynergia, and decreased sensation can be detected.⁶⁵ In patients with abnormal urodynamic testing, whether clinically symptomatic or asymptomatic, improvement from 29% to 75% has been reported following detethering in a broad range of patients. Urodynamic tests have been used as a marker to document improvement or stability of function following a detethering procedure.

Surgery

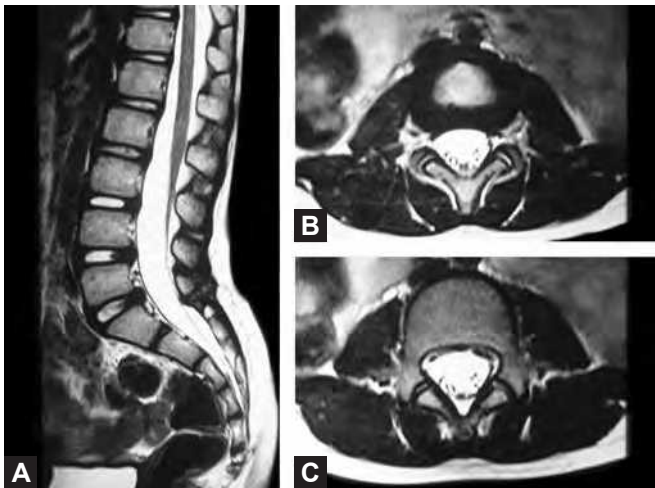
The most common age at presentation is between 5 and 9 years, concurrent with the period of rapid growth. Untethering involves the release of filum terminale between the L5-S1 or S1-S2 interlaminar space. This is fairly a safe surgery in experienced hands and best operate under microscope to visualize the film.⁶⁶ The film is differentiated from the roots by the pale color and a single tortuous vessel that runs on it with a tether (Fig. 20.24). The aim of the surgery is to deal with the local pathology; however, recurrent tethering can produce symptoms. In adult population, the rate of retethering has been quoted to be as high as 25%. It aimed to prevent further neurological deterioration and to allow functional improvement. Untethering can improve back and leg pain in 78% and 83%, respectively. However, motor weakness will stabilize or improve in only 27% and 64% of patient, respectively. Sensory deficits remained unchanged in 50% of patients. Urological abnormalities improved in 50% of patients undergoing unfettering and remained stable in 45%.⁶⁶ Untethering of the spinal cord after a previous myelomeningocele repair is, however, challenging because the structural and functional anatomy is distorted due to both developmental anomalies and scar from previous surgery. The placode and functional nerve roots can be difficult to distinguish from scar, which can be, tethered themselves, placing the patient at significant risk of neurological deterioration from the procedure.⁶⁷ It is imperative that symptomatic secondary tethered cords are recognized early because delayed recognition is associated with irreversible injury (Fig. 20.27). Although, radiographically demonstrated spinal cord tethering occurs in nearly all patients after repair of spinal dysraphisms, not all patients are symptomatic. Retethering of the cord has been considered to be very rare. The risk of tethering can vary according to the patient's age, the type, and the severity of the entire condition. In children the risk of retethering is higher (20%) compared to adults (5–10%) due to the shallow canal.



Fig. 20.24: Thickened and tethered filum terminale seen extending up to S3 level. The sacral nerves are seen.



Fig. 20.25: Patient presented with leg pain and bladder symptoms at 6 years of age. Lower back shows a hairy patch and the patients magnetic resonance imaging scans are shown in Figures 20.26A to C.



Figs. 20.26A to C: Magnetic resonance imaging scan of the patient above shows low lying cord below L3 (A) and thickened film terminale (B and C) measuring >2 mm attached at S3 level.



Fig. 20.27: Secondary tethered cord syndrome in a patient with a myelomeningocele. L4–L5 spina bifida seen with low-lying cord and neural elements attached with bony defect within a lipomatous lesion.

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Occult Spinal Dysraphism and Tethered Spinal Cord

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Snapshot

- » Lipomas/Lipomyelomeningocele
- » Split Cord Malformations
- » Dermal Sinus
- » Tethered Cord Syndrome

INTRODUCTION

Occult spinal dysraphism (OSD) refers to a group of disorders arising as a result of incomplete formation of the midline dorsal neural, mesenchymal, and cutaneous ectodermal structures during embryogenesis. Depending on which embryonic layer is involved, there can be abnormalities in the skin or osseous or neural elements. The term “occult” is used to distinguish these lesions from the open group of neural tube defects called spina bifida aperta (e.g. myelomeningocele). The term “occult,” however, is misleading due to the fact that the majority of these conditions are associated with some abnormalities of the overlying skin. The OSD has come to encompass a large group of lesions that include lipomas, lipomyelomeningoceles, split cord malformations (SCMs), dermal sinus tracts, neurenteric cysts, dermoids, and tight terminal filum.

One of the most common associated syndromes with OSDs is tethered cord syndrome (TCS). Spinal dysraphisms can limit the normal rostral movement of the spinal cord during development and lead to traction on the spinal cord. This may cause progressive neurologic, urologic, and orthopedic deterioration. The focus of this chapter will be on the various common forms of OSDs and the clinically associated syndrome of the tethered spinal cord.

LIPOMAS/LIPOMYELOMENINGOCELE

Spinal cord lipomas are among the most common single dysraphic lesions that often present with TCS. The incidence

of lipomas has been reported to be one in 4,000 live births.¹⁻³ They are responsible for approximately 25–30% of cases of the tethered cord in children.^{4,5} Spinal cord lipomas tether the spinal cord because they are attached to the neural elements and the subcutaneous fat, posterior elements, or thoracolumbar fascia through a defect in the dura (Fig. 21.1).

There are several different types of spinal cord lipomas: those that involve the conus and those that involve the filum. Chapman’s classification system divides spinal cord lipomas into three categories: dorsal, transitional,

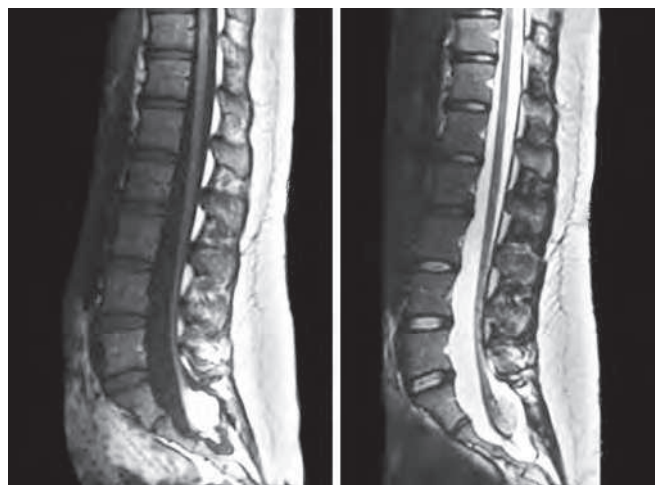


Fig. 21.1: T1 (left) and T2 (right) magnetic resonance imaging of the lumbar spine demonstrating a lipomyelomeningocele, low-lying conus and tethered cord.

and terminal.⁶ Dorsal and transitional lipomas contain a stalk that extends from the normal subcutaneous fat through a dorsal midline defect in the posterior elements (lamina), lumbodorsal fascia, and dura to attach directly to the spinal cord. In dorsal lipomas, the stalk inserts dorsally into the spinal cord with normal dura and cord caudal to it. However, in transitional lipomas, the stalk blends into the terminal conus with no normal cord caudal to it. Terminal lipomas attach to the most distal part of the conus with the lipoma either replacing the filum completely or separating it from the conus by a thickened filum. The dura and lumbodorsal fascia are intact with the sacral roots exiting the conus above the lipoma.^{6,7}

Transitional lipomas are the most common type of lipomyelomeningocele, representing approximately 64–75%, while terminal lipomas account for approximately 13–26% of all spinal cord lipomas.^{8,9} The rarest are the dorsal lipomas that are found in <10% of all cases.

The embryologic defect responsible for spinal lipomas occurs between the time of primary neurulation (neural tube closure) and secondary neurulation (formation of the terminal spinal cord). Differences in the timing and location of the defect are thought to lead to different spinal lipomas. The error is believed to be premature dysjunction between the cutaneous and neural ectodermal layers prior to the neural tube closure. Mesenchymal cells migrate through the focal site, prevent further closure of the neural tube, and differentiate into a lipomatous mass.¹⁰ Dorsal lipomas are thought to be a result of a transient interruption of the primary neural tube closure, resulting in a segmental abnormality. On the contrary, the complete involvement of the entire conus in transitional lipomas suggests that not only is primary neurulation involved, but that secondary neurulation is also affected. The rostral part of the transitional lipoma arises from aberrant primary neurulation, whereas the caudal part arises from abnormal secondary neurulation. In terminal lipomas, the error is believed to be in secondary neurulation because the segments formed during primary neurulation (above S2) are not involved and there is no dorsal dural defect. Also, the lipoma is part of or replaces the filum, which is formed during secondary neurulation.¹¹

Lipomas and lipomyelomeningoceles can cause neurologic dysfunction by abnormally forming neural structures, mass effect on the spinal cord, or traction by tethering the spinal cord to the surrounding structures during development.¹² Children with spinal cord lipomas tend to present with neurologic deficits by 2 years of age.¹³



Fig. 21.2: Photograph demonstrating hypertrichosis of the lumbosacral region.

These patients often deteriorate or become symptomatic during periods of rapid growth or activities that stretch the spine.⁵ These include activities where there is a disproportionate lengthening of the vertebral column in relation to the spinal cord that is tethered. Also, direct trauma to the subcutaneous portion of the lipoma can result in severe pain and dysesthesias, followed by neurologic deficit.¹³

Cutaneous abnormalities indicative of lipomyelomeningoceles or lipomas often occur in the midline of the back near the level of the spinal lesion. They include subcutaneous lipomas, capillary hemangioma, skin dimples, hairy patches, and skin appendage¹³ (Fig. 21.2). The incidence of cutaneous stigmata in patients with spinal cord lipomas is about 70%.¹ Subcutaneous lipomas are present in about 60% of cases of lipomyelomeningoceles.^{14,15} About 20–30% of intradural lipomas are associated with cutaneous stigmata without an obvious subcutaneous lipoma.¹³ In contrast to dorsal and transitional lipomas, terminal lipomas are the most likely to have no cutaneous stigmata of spinal dysraphism.¹⁶

Neurologic deficits, urologic dysfunction, and orthopedic deformities are commonly seen with spinal lipomas. Motor deficits can present in infants, toddlers, and older children. They can present as asymmetric movements, atrophy of muscles, delay in motor milestones, or discrete muscle weakness.¹³ Although one side tends to be worse, both sides are affected. Bowel and bladder dysfunction is commonly seen in patients with spinal cord lipomas. Urodynamic testing may reveal abnormalities in 33–66% of children younger than 1 year of age.¹¹ Common symptoms

include delayed toilet training in younger children and urgency, frequency, and poor voluntary control in older children. The most common urodynamic abnormalities are flaccid bladder, detrusor sphincter dyssynergia, and detrusor hyperreflexia.^{14,17} Orthopedic abnormalities include foot deformities, asymmetric leg length, hip subluxation, scoliosis, and vertebral anomalies.¹¹ Progressive foot deformities are one of the most common presenting features of children with spinal cord lipomas.^{18,1,19} They include hammertoe deformity, varus or valgus deformity, exaggeration of arches, asymmetric foot size, and trophic foot ulceration. Scoliosis is seen in 10–25% of patients with spinal lipomas.^{11,13} This form of scoliosis, which is usually related to tethering of the spinal cord, lacks the rotational deformities that are seen with vertebral body anomalies.¹¹ In patients with congenital scoliosis, 18% were found to have OSD.²⁰ Congenital spinal defects can involve the laminae, pedicles, disc spaces, vertebral bodies, and the size and number of vertebrae. It is recommended that the spinal cord be detethered prior to any deformity correction of the spine to prevent neurologic deterioration.

The natural history of spinal lipomas has not been well delineated. However, most pediatric neurosurgeons would advocate surgical intervention for symptomatic patients regardless of the type of lipoma.^{8,9,17} In these instances, the patient's symptoms either stabilize or improve. In asymptomatic patients, the recommendations are not so clear. Some authors advocate prophylactic surgery in an attempt to prevent neurologic deterioration in the future.^{14,15,8,17} Two main reasons to support this view are a direct relationship between progressive neurologic deterioration and increasing age, and an 85% deterioration rate in children with untreated lipomas by 5 years of age.^{15,21} On the contrary, some authors advocate observation only for asymptomatic patients since the natural history is not evident and the associated surgical morbidity is high.^{22,9} Once the decision to operate has been made, the two primary objectives of surgery are to detether the spinal cord and reduce the mass effect by debulking the lipoma. These procedures have been made more safe with the use of intraoperative neuromonitoring and the laser.

SPLIT CORD MALFORMATIONS

Split cord malformation is a rare closed neural tube defect where the spinal cord is split into two halves of variable size. It is an occult form of spinal dysraphism in which the intervening tissue between the split cord causes tethering

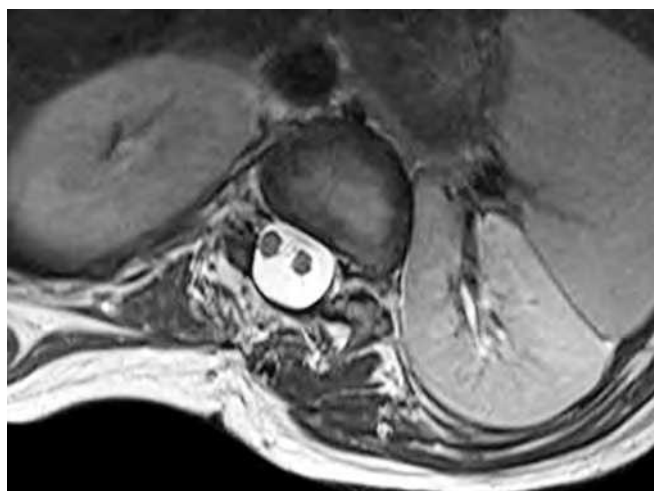
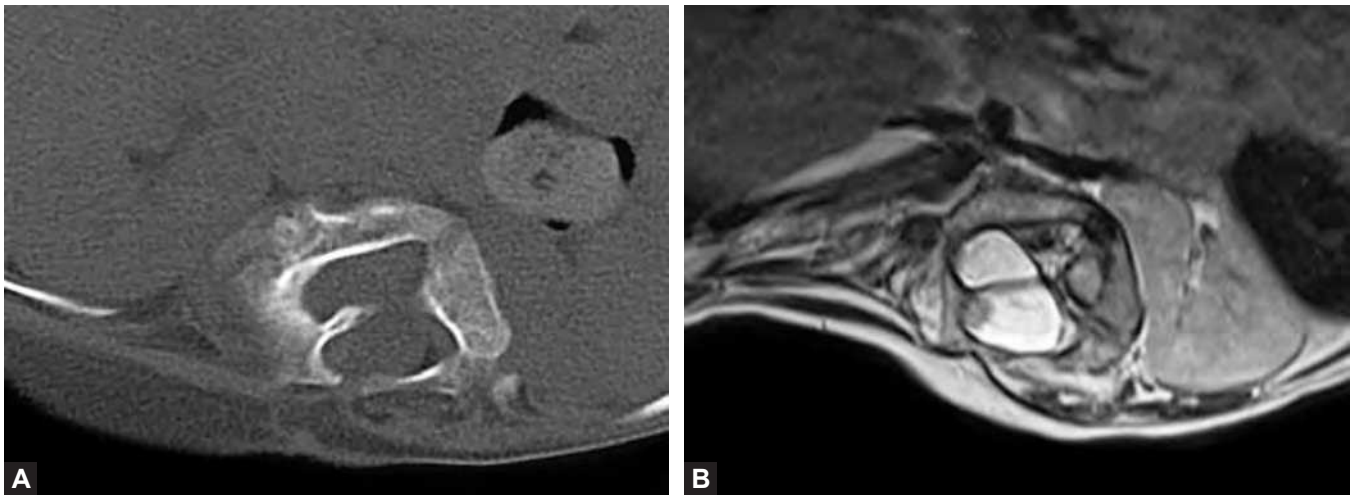


Fig. 21.3: Axial T2 magnetic resonance imaging demonstrating type II split cord malformation with two hemicords in one dural sleeve.

of the spinal cord. This may lead to progressive neurologic, urologic, or orthopedic deterioration.

According to Pang, SCM is believed to be caused by an error of development during the time that the primitive neurenteric canal closes. There is formation of an abnormal accessory neurenteric canal connecting the yolk sac to the amnion through the midline embryonic disc that splits the notochord and neural plate. This canal then forms an endomesenchymal tract that splits the spinal canal longitudinally for a short distance. The tract develops into a midline septum, and the tissue surrounding the tract forms into two hemicords.²³

Split cord malformations have been divided into two main categories based on the number of dural tubes and the composition of the intervening midline septum. According to the Pang's classification, SCMs are of two types based on the composition of the dural coverings and intervening tissue.^{24,25} In SCM type I (formerly known as diastematomyelia), there is an extradural bony or fibrocartilaginous spur that divides the spinal cord into two halves with two different dural sleeves. In SCM type II (formerly known as diplomyelia), there is no bony septum but an intradural fibrous band and a common dural sac (Fig. 21.3). The type I septum almost always extends directly anterior to posterior.^{26,27} On the contrary, the type II septum is often obliquely or even coronally directed, dividing the anterior and posterior hemicords. In both types of SCM, the septum is the most caudal margin of the split with hemicords that can extend rostrally for many segments above the septum. Type I SCM is often



Figs. 21.4A and B: Axial CT (A) and axial T2 magnetic resonance imaging (B) demonstrating type I split cord malformation with two hemicords and two dural sleeves with an intervening bony septum.

associated with bony abnormalities, such as bifid vertebral bodies or congenital bony fusion (Figs. 21.4A and B). Type II SCM is the bony anatomy that is usually normal. Type I SCM is usually found in the thoracolumbar spine, whereas type II SCM can be seen anywhere.²⁵

Split cord malformation can be associated with scoliosis and other intraspinal anomalies. Congenital scoliosis is the most common clinical manifestation and is associated with 60–84% of patients with SCM.^{28,29} Common anomalies found are syringomyelia, myelomeningocele, lipoma, teratoma, neurenteric cyst, and low-lying conus.^{30–34} Secondary to these features, magnetic resonance imaging (MRI) should be performed in all patients with SCM or atypical scoliosis. Atypical scoliosis consists of left thoracic curves, a large curve at a young age, associated pain or neurologic deficits, thoracic kyphosis $>40^\circ$, or less rotation than is expected.^{35–39}

There are many cutaneous stigmata of SCMs, including hairy patch, capillary hemangioma, and dermal sinus tract. The most common is a large patch of hair overlying the defect (called “fawn’s tail”) and can be found in over half of all patients with SCM.^{40,41,25} Patients with SCM also have associated abnormalities of the musculoskeletal system, including scoliosis, asymmetry of the lower extremities, and cavus foot.

The clinical presentation of SCM differs in children from that in adults. In children, the onset is slow and insidious progressive neurologic deterioration. They can have painless loss of sensorimotor function, weakness of extremities, spasticity, and difficulty with ambulation.²⁵ In adults, SCM usually presents suddenly after an event, such

as a fall with dysesthesia or, less frequently, weakness. Bladder involvement in the form of urgency, frequency, or recurrent urinary tract infections is also commonly seen.^{42,43}

The indications for surgical intervention of SCM include any sign of tethered cord or neurologic compromise since the symptoms are usually progressive. In children with SCM, the risk of neurologic and orthopedic problems arising increases with age. For this reason, some authors advocate that the spines of all young children with SCM should be surgically explored.^{44,25} Prior to any surgical intervention, a computed tomography (CT) and MRI should be performed to provide a good understanding of the size and shape of the septum and vertebral body anomalies and to rule out any additional tethering lesions.

DERMAL SINUS

Dermal sinus tracts are the most representative of all OSD lesions. Spinal dermal sinus tracts consist of an epithelial-lined tract extending from the skin surface to the spinal fascia, dura mater, or spinal cord. These lesions may be found anywhere along the midline of the neural axis, although the lumbar and sacral areas are the most common. They are often confused and difficult to distinguish from benign congenital dimples. The incidence of dermal sinus ranges from 3% to 36%.⁴⁵ They can be solitary or combined with other manifestations of dysraphism. Dermal sinus tracts can be found in 15–40% of SCMs.²⁵

Dermal sinus tracts are often associated with tumors that can be found anywhere along the sinus tract. They in-

clude dermoids, epidermoids, and teratomas. Tumors can be found in 60% of all patients with dermal sinus tracts, with dermoids being the most common (83%).⁴⁶⁻⁴⁸ In addition, any element of cutaneous ectoderm can also be found along the tract, such as sweat glands, sebaceous glands, and hair follicles.

Dermal sinus tracts are remnants of incomplete neural tube closure. They result from incomplete separation of neural ectoderm from epithelial ectoderm, also called incomplete dysjunction. Dermal sinus tracts are unusual in that they occur after primary neural tube closure. The failed separation between the cutaneous ectoderm and neural ectoderm results in a tubular tract as the remaining vestige of the connection between these two layers. Because the neural tube closure was completed normally, the brain and spinal cord are usually well-formed and the child is neurologically normal at birth.

Like all other OSDs, dermal sinus tracts are also associated with cutaneous stigmata (Fig. 21.5). The six most common cutaneous findings associated with dermal sinus tracts include cutaneous dimple or pit, flat capillary hemangioma, hairy patch, dorsal dermal appendage, subcutaneous lipoma, and atretic meningocele.⁴⁹⁻⁵² True dermal sinus tracts can be found anywhere along the midline of the neuroaxis. However, the majority of these lesions are located in the lumbar or sacral areas. Tracts in the cervical and thoracic spine make up only 11% of all cases.⁵³

Dermal sinus tracts can often be confused with benign congenital sacroccygeal dimples. Simple dimples that are <5 mm in diameter, midline in location, overlie the coccyx, are hidden deep within the gluteal cleft, and are within 2.5 cm of the anus are not associated with OSD. However, 40% of atypical dimples such as those >5 mm in diameter, >2.5 cm from the anus, or associated with other cutaneous stigmata are associated with OSD.⁵⁴

The clinical presentation of dermal sinus tracts is usually infection or tethered cord. Infections can manifest as meningitis, draining tracts, or even intramedullary spinal cord abscesses.⁵⁵ Almost all of the spinal cord tethering occurs with dermal sinus tracts that are located in the lumbar or sacral areas.⁵⁶ Symptoms can include back pain, radiculopathy, weakness, sensory deficits, bowel or bladder changes, and foot deformities.

Once a dermal sinus tract is identified, surgical exploration and excision are recommended. Preoperative imaging, such as CT or MRI can be useful in identifying any intradural lesions or masses. It can also help delineate the extent of the tract course. In infants <6 months of



Fig. 21.5: Photograph demonstrating the cutaneous lesion in a patient with a dermal sinus tract.

age, ultrasound can be a very useful screening tool. It is portable, noninvasive, requires no sedation, and takes advantage of the cartilaginous vertebral arches in the infant.⁵⁷ The goals of surgery are to disconnect the neural elements from the skin surface, avoid infection, detether the neural elements, and excise any intradural masses.

TETHERED CORD SYNDROME

The term “tethered cord syndrome” was initially used to describe when an abnormally short and thickened filum terminale causes the conus medullaris to become caudally displaced.¹⁹ Currently, the term is used to describe any progressive neurologic, urologic, or orthopedic problem caused by a spinal dysraphism that limits the normal rostral movement of the spinal cord during development.¹⁵ The underlying pathophysiology for spinal cord tethering is mechanical traction that causes damage in a cumulative and insidious pattern. Spinal cord traction impairs mitochondrial oxidation and disrupts axonal transport that makes it susceptible to injury.⁵⁸⁻⁶⁰

The TCS can be divided into two main groups: congenital and acquired. Congenital TCS is described in the setting of OSDs where a lesion tethers the spinal cord during normal development. Some examples include lipomas/lipomyelomeningocele, dermal sinus tracts, and SCMs. Acquired TCS occurs following surgical repair of a myelomeningocele, infection, or trauma that may lead to scar formation and tethering of the spinal cord. Regardless of the etiology, free and rostral movement of the spinal cord is restricted with mechanical traction.

The clinical presentation of TCS is variable. Some children are completely asymptomatic but come to medical attention for the midline cutaneous stigmata identified on their back. Some examples of these include sacral dimple, capillary hemangioma, hypertrichosis (hairy patch), subcutaneous lipoma, gluteal asymmetry, or skin appendage. These are often the signs of OSDs. Some of these lesions can be pathognomonic for certain OSD. For example, hypertrichosis occurs in 65% of type I SCMs and subcutaneous lipomas or skin appendages occur in about 80% of spinal lipomas.^{9,61}

Neurologic symptoms that occur in patients with OSD range from simple back or leg pain to weakness and sensory deficits. Motor and sensory deficits are often subtle and progressive in nature. Some early signs may be delay in walking, unilateral atrophy of leg muscles, or an intorted foot. One common feature of neurologic deficits is that they are usually asymmetric regardless of the type or location of the spinal lesion.⁶² Spasticity, increased tone, and hyper- or hypoactive reflexes may be present.

Urologic and bowel dysfunction are common presenting symptoms of OSD. In older children and adults, the most common presenting urologic complaints are frequent urinary tract infections, urgency, frequency, enuresis, and incontinence. Urologic dysfunction is reported in about 70–87% of children with OSD. Common presenting scenarios include delayed toilet training, enuresis, and recurrent urinary tract infections. Fecal incontinence and constipation may also coexist with the urological abnormalities.^{63–66}

The most common orthopedic deformities associated with TCS include bifid spines, butterfly vertebrae, hemivertebrae, deformities of the lower extremity, and scoliosis.^{9,67,68} Unilateral or bilateral foot deformities include club feet, varus or valgus deformities, and clawing of the toes. Scoliosis is a common manifestation of OSD and TCS. Patients with progressive or atypical features with their scoliosis should be screened for OSD and TCS. Atypical scoliosis consists of left thoracic curves, progression of curve magnitude $>10^\circ$ per year, a large curve at a young age, associated pain or neurologic deficits, thoracic kyphosis $>40^\circ$, or less rotation than is expected.^{35–39} Surgical correction of scoliosis has a significantly higher risk in patients with neurologic etiologies than those with idiopathic scoliosis.⁶⁹ Many surgeons advocate neurosurgical treatment prior to any deformity corrective procedure; indications include cranial nerve deficits, cerebellar findings, motor or sensory deficits, and pain or headache.⁷⁰

KEY POINTS

- Occult spinal dysraphism (OSD) refers to a group of disorders arising as a result of incomplete formation of the midline dorsal neural, mesenchymal, and cutaneous ectodermal structures during embryogenesis.
- Spinal cord lipomas are among the most common single dysraphic lesions that often present with tethered cord syndrome.
- Dermal sinus tracts are often associated with tumors, such as dermoids, epidermoids, and teratomas, which can be found anywhere along the sinus tract.
- Cutaneous stigmata of OSD include sacral dimple/pit, capillary hemangioma, hypertrichosis (hairy patch), subcutaneous lipoma, gluteal asymmetry, or skin appendage.
- Occult spinal dysraphism and tethered cord syndrome can cause progressive neurologic, urologic, and orthopedic deterioration.

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Surgical and Nonsurgical Treatment of Myelomeningocele and Associated Anomalies

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Snapshot

» Myelomeningocele (Open Spinal Dysraphism)

INTRODUCTION

Myelomeningocele is considered the most common neural tube defect (spinal dysraphism). Neural tube defects encompass a heterogeneous group of congenital anomalies of the brain and spinal cord, arising at various gestational ages. Neural tube defects are further divided into open (neural tissue exposed to the surface) and closed (skin covered) lesions. Open neural tube defects arise during the process of neurulation, between days 17 and 30 of gestation. Open spinal dysraphism includes three categories of neurulation defects: craniorachischisis (total dysraphism), anencephaly, and myelomeningocele.

The aim of this chapter is to review the contemporary treatment protocols of myelomeningocele with emphasis on its pathogenesis, prevention, prenatal and postnatal management, as well as conservative and surgical treatment options of the frequently associated spinal deformities. The more common spinal deformities found in this patient population are scoliosis, which occurs in 20–94% of patients^{1–3} depending on the level of the neural deficit and ambulatory status; kyphosis, which occurs in 8–20% of patient⁴; and final pelvic obliquity, which can be caused by supra-, intra-, or infrapelvic etiology.

MYELOMENINGOCELE (OPEN SPINAL DYSRAPHISM)

Pathogenesis

The different types of neural tube defects all represent deviations from the normal development of the spine and the

spinal cord.⁵ Basic knowledge of the normal spinal embryology allows for a better understanding of the clinical presentation, associated anomalies and therapeutic options of these lesions. The process of gastrulation, usually occurring during the third week of gestation (days 16 and 17 of gestation), converts the bilaminar embryo into a trilaminar model, consisting of the future mesoderm, ectoderm, and endoderm.⁶ The endoderm will give rise to the gut structures, the mesoderm to the striated muscles and skeleton, and the ectoderm to the skin and nervous system.⁵ Most of the current morphological and molecular knowledge of neural tube development is derived from animal studies, mainly from the *Xenopus*, chick and mouse embryos.^{7–10} Neurulation, the process of neural tube formation, is further divided into primary and secondary neurulation. During primary neurulation, notochordal induction stimulates at day 17 the overlying ectoderm layer to differentiate into the neural plate on the dorsal midline of the embryo. The neural plate will fold in upon itself to form the neural groove, a shallow midline crease just above the midline notochord visible on days 17–19. The neural groove continues to deepen with development of the neural folds laterally, which will elevate and then converge medially to close the neural tube. This closure process occurs during a 4- to 6-day period and involves the separation of the cutaneous ectoderm from the neuroectoderm (disjunction).⁸ The cranial part of the spinal cord (cranial neural tube) is the first part of the neural tube to close in a discontinuous manner through four waves of closure along the craniocaudal axis.^{11–13} The caudal neural tube closes linearly through one last wave of closure from

the point of initial contact at the cranial spinal cord to the caudal (posterior) neuropore, which closes at 25–27 days of gestation at a site located below the last visible somite at this embryologic stage. Closure of the caudal neuropore represents the last stage of primary neurulation, the process that is responsible for the formation of the majority of the spinal cord as far distal as S2. The terminal filum and probably the inferior sacral spinal cord are formed by secondary neurulation.^{8,14,15} During this last process, a mass of pluripotent cells at the caudal embryonic pole [called the caudal cell mass (CCM)] gives rise to the secondary neural tube and vertebrae caudal to S-2.

The embryogenesis of neural tube defects represents disorders of the primary neurulation. Failure of closure of the cranial neural tube (wave 2) is thought to be responsible of anencephaly. Myelomeningocele is generally thought to be caused by failure of closure of the caudal neuropore (junction of waves 4 and 5, corresponding to the junction of primary and secondary neurulation).^{8,16} This initially proposed nonclosure theory is the most widely accepted and supports the concept that neural tube defects are caused by a primary failure of neural tube closure. It probably accounts for the majority of clinically encountered cases. A second fundamental theory was secondarily developed and also supports a disorder of primary neurulation. This overdistension theory proposed that overdistension and rupture of a previously closed neural tube is responsible of neural tube defects embryogenesis. This last model may play a role in some experimental neural tube defect models.^{17,18} In addition, it was more recently proposed that some forms of complex spinal dysraphism could be the result of a failure occurring during gastrulation and leading to the formation of paired notochords, each developing into a hemicord. These double anlagen will in turn secondarily affect neurulation and induce either a hemimyelomeningocele (if neurulation is disrupted in only one hemicord) or a myelomeningocele associated with a split cord malformation (if primary neurulation fails in both hemicords).^{19,20} Finally, the embryogenesis of the Chiari II malformation, almost invariably associated with myelomeningocele, is thought to take place at a later stage of gestation. It could be linked to an abnormal development of the ventricular system because of the open neural tube defect, and this would account for the extensive constellation of anomalies seen in patients with Chiari II.^{21,22}

With the nonclosure of the neural tube, there is no disjunction of the cutaneous ectoderm from the neuroectoderm. This leaves the cutaneous layer connected laterally

to the neuroectoderm. Similarly, the associated mesoderm, including somites, develops in a lateral position forming the mesenchymal elements of the spinal canal. Consequently, at the level of the defect, the neural tissue is everted, the laterally located laminae are bifid, and the vertebral pedicles are rotated outward. Advanced rotation of the pedicles will turn the paraspinal muscles into flexors of the spine rather than extensors by displacing them anteriorly to the vertebral bodies, further aggravating a kyphosis.⁵

The neurological deficits observed in open spinal cord defect could represent the results of a two hits injury process. The first one is the malformation of the neural tube by itself and its associated structural defects. The second hit could be linked to the direct exposure of the spinal cord tissue to amniotic fluid.^{23,24} Experimental studies demonstrated the damage associated with exposure of the neural tissue to the amniotic fluid. In animal models, exposure of the spinal cord to amniotic fluid through opening of the dura was associated with neurological deficits ranging from weakness to lower limbs deformity, together with necrosis and erosion of the exposed spinal cord on histologic analysis. Using the same types of animal models, in utero closure of the defect was associated with improvement of the neurological function and of the histologic appearance.^{23,25,26}

Etiology, Epidemiology and Prevention

The exact etiology of neural tube defects is most probably intricate, and it remains currently poorly understood despite numerous advanced clinical, epidemiological and experimental studies.⁹ It is generally accepted that most cases of nonsyndromic myelomeningocele are of multifactorial origin, which is the result of complex interactions between genetic and environmental risk factors.^{27–29} Taken independently, these risk factors may play a contributive rather than a causative role to open neural tube defects.

Regarding relevant environmental factors, maternal hyperthermia, antiepileptic treatment with valproic acid during pregnancy and some nutritional deficiency or excess have been associated with a significant increase in the incidence of neural tube defects.^{7,9} Among nutritional factors, the role of folic acid is of primary importance, given its impact on prevention, and it will be discussed in great depth later in this section.³⁰

Most neural tube defects are isolated malformations, and they are potentially presenting with associated systemic congenital anomalies.³¹ These defects tend to demonstrate familial aggregation but do not follow a strict

Mendelian pattern of inheritance.^{7,9} The recurrence rate in families with an affected member is increased, with a recurrence risk for neural tube defects in siblings of patients with myelomeningocele ranging from 2% to 5%.³² The occurrence of neural tube defects among first- and second-degree relatives of an affected member was demonstrated to be significantly higher than the incidence reported in the general population. It was estimated as 3.2%, 0.5% and 0.17% in the United States for first-, second- and third-degree relatives of probands, respectively.³³

Neural tube defects may occur more rarely as part of a syndrome involving chromosomal or single-gene disorders with autosomal dominant, recessive, and sex-linked recessive inheritance patterns. In these cases, the malformation is associated with other nonrelated congenital abnormalities.³¹ These birth defects can also be associated with nongenetic syndromes.³⁴

The overall incidence of myelomeningocele is considered to be 1/1,000 live births.³¹ Many studies demonstrate some geographic and ethnic variations. The incidence of neural tube defects has clearly decreased in certain areas, partly because of prenatal diagnosis and elective terminations.^{35,36}

The primary prevention of neural tube defects today remains folic acid supplementation or fortification during the periconceptional period.³⁷ Unfortunately, anencephaly and myelomeningocele originate during the first month after gestation and many women do not even know that they are pregnant at this time. Ideally, women should have enough folic acid in their system before conception.³⁸ Periconceptional supplementation with folic acid alone or multivitamins (containing folic acid) has been associated with a 40–80% reduction in the risk of neural tube defects in intervention studies.^{39–41} In addition, the results of the observational studies and randomized clinical trial studies have also suggested that folic acid could prevent major birth defects other than those in the neural tube.^{42–44}

Many health organizations worldwide have issued recommendations for women of reproductive age to maintain a healthy diet and to take folic acid supplements. They should take 0.4 mg (400 mg) of synthetic folic acid daily in addition to consuming foods with a high concentration of folate derived from a varied diet, when planning a pregnancy.^{45,46} An increased dose (4–5 mg) of periconceptional folic acid supplementation is recommended when there is a history of neural tube defects in either a personal case or when there has been some family history.^{37,38} Despite awareness and political efforts to promote folic acid supplementation, a substantial proportion of women

of childbearing age are not implementing these recommendations. At-risk groups are those of a young age, with a lower level of education and women with unplanned pregnancies.^{37,47–55} A way to solve this problem could be to fortify foods with folic acid.⁵⁶ Some countries have opted for either voluntary or mandatory fortification of foods in addition to the promotion of folic acid supplemental use, which have shown beneficial effects.³⁷ The secondary prevention of neural tube defects relies on prenatal diagnosis, which is discussed later in this chapter.

Presentation (Including Associated Abnormalities)

Myelomeningocele is probably one of the most dramatic congenital defects compatible with life.⁵⁷ At birth, an irreversible neurological deficit of various extents depending on the level of the lesion is almost always present.³¹ The neurological function of the child has to be carefully evaluated and documented. The neurological examination is challenging usually with abnormal reflexes and occasionally spinal shock.⁵⁸ Asymmetry in neurological deficits is frequent in myelomeningocele but can be a sign of an associated spinal malformation such as diastematomyelia; hence, complete imaging of the spinal cord is mandatory.⁵ Motor denervation level is evaluated by applying a sharp stimulus to the upper extremities (or an unaffected area of the trunk) and observing the lower extremities for spontaneous motion. The level of sensory function is determined while examining the child when he is quiet or sleeping. A painful stimulus is applied from distal to proximal watching for a facial rictus or cry.⁵ The patient is usually found paraplegic at birth, since most of the defects take place at the thoracolumbar spinal level. The level of neurological deficiency moves distally as the lesion level is located more caudally. Patients with sacral lesions present often with only neurogenic bladder and subtle foot deformities.^{59–61}

The goal of the surgical primary closure of the myelomeningocele is to protect and maintain neurological function and prevent infection.⁵ Thereafter, careful monitoring of the affected child is mandatory to prevent further worsening of the neurological deficit secondary to the associated spinal deformity that can be present with myelomeningocele.³¹ These associated abnormalities include mainly Arnold-Chiari malformation, hydrocephalus and a tethered spinal cord.

The Arnold-Chiari malformation, also known as the Chiari II malformation, actually comprises multiple anomalies affecting the brain, skull and spinal cord to a varying

extent.⁶²⁻⁶⁵ The main anomaly is displacement to varying degrees of the cerebellum, pons and medulla in the cervical canal with a small posterior fossa, leading to a variable degree of compression of the brainstem despite enlarged foramen magnum and upper cervical canal.⁵ Possible associated findings include kinking of the cervicomedullary junction, brainstem nuclei changes, tectal beaking in the upper brainstem and low-lying tentorium. In addition, abnormalities of the corpus callosum, the enlargement of the thalamic massa polimicrogyria and the gray matter heterotopias may be noted in the supratentorial compartment.^{5,31} Associated respiratory and swallowing disturbances are initially observed and are the most frequent, but in most cases, they tend to be moderate and to resolve themselves spontaneously. Severe brainstem dysfunction syndrome is rare and is associated with generalized hypotonia and nasal regurgitation because of a severe swallowing disturbance, vocal cord palsy and central dyspnea. In these cases, magnetic resonance imaging (MRI) studies reveal severe Chiari II malformation with a very small posterior fossa and hydrocephalus. First line of treatment is management of hydrocephalus with a ventriculoperitoneal shunt placement, but foramen magnum decompression through suboccipital craniectomy that is associated with a laminectomy may sometimes be required.⁶¹

Most of the children with myelomeningocele present and with hydrocephalus either at birth or more frequently after the closure of the neural tube defect.⁶⁶ The contributing factors of hydrocephalus in these patients are mainly the presence of a forked and/or stenotic aqueduct of Sylvius and with the obstruction of cerebrospinal fluid (CSF) outflow from the fourth ventricle because of the small posterior fossa related to the Chiari II malformation.^{67,68} Despite these anatomic anomalies, the enlargement of the ventricles is frequently only mild to moderate, initially.⁶⁶ Surgical closure of the neural tube usually accelerates ventricular dilatation by stopping the decompression of the CSF into the myelomeningocele sac. Bulging fontanelles, altered mental status, nausea and headaches are signs of acute hydrocephalus in children.^{31,69} The preferential treatment of hydrocephalus is with the placement of a ventriculoperitoneal shunt. The ventriculoatrial shunt treatment is reserved for selected cases, whereas there seems to be no room for endoscopic third ventriculostomy in the treatment of hydrocephalus associated with myelomeningocele.^{61,70,71} There are some controversies regarding the timing for the placement of the shunt. Doing this procedure concomitantly with the closure of the neural tube

prolongs the surgical time and may increase the risk of shunt infection. Some surgeons prefer, whenever possible, to postpone shunt placement at least until 1 week after the myelomeningocele has been repaired. At birth, however, some infants present themselves with a significant hydrocephalus and they require a shunt placement at the time of neural tube defect closure.^{21,61,66,72-77} Not delaying the shunt placement when indicated is of primary importance, since hydrocephalus is one of the main coexisting pathologies responsible for morbidity and unfavorable outcome in patients with myelomeningocele.⁵⁷ Unfortunately, the rate of shunt revision is non-negligible and can be necessary in up to half of the shunted children during their first year of life. Then, however, the rate of revision decreases to approximately 10% per year.⁷⁸

After the primary repair of the neural tube defects, late neurological deterioration is mostly caused by another potentially treatable cause, the so-called "tethered cord syndrome."⁷⁹ It occurs when the spinal cord is fixed by a stiff structure and the conus medullaris is located at an abnormally low level. During normal development, the level of termination of the spinal cord gradually ascends from L4-5 at 20 weeks of gestational age, L3 at 30 weeks, to the adult level of L1-2 at 2 months of postnatal age.⁸⁰ Radiographically, the spinal cord is generally considered tethered when the conus tip is located below the lower border of the L2 vertebral body. Historically, a computed tomographic myelogram was obtained looking for a thickened filum terminale, measuring >2 mm.⁸¹ With the advent of MRI, new radiological diagnostic criteria have been put forth: location of the conus tip being below the L1-2 disc space, the diameter of the filum terminale >1 mm, or fatty thickened filum alone might be considered sufficient diagnostic criteria.³¹ Of note, children with myelomeningocele are considered to all have "tether cord"; these radiographic criteria are not diagnostic by themselves, since most of these patients will have a low-lying conus medullaris.⁸² Hence in these children, clinical findings and exam are paramount as to their management. Before assuming that new neurological deficit is from retethering, one must exclude other possible factors known to cause progressive deficit in myelomeningocele patients (Chiari II or shunt dysfunction, or hydromyelia). The most common presenting symptoms of tethered cords include weakness, deterioration in gait endurance, back pain, progressive scoliosis, progressive orthopedic deformities of the lower extremities such as cavus feet, and urinary incontinence. Magnetic resonance imaging will then help precise the

exact cause of tether and further appreciate the presence of additional associated pathologies, such as dermoid tumors, hydromyelia, and diastematomyelia.^{31,79} Early release of the tethered cord is associated with stabilization or improvement of the presenting complaints in most of the patients with myelomeningocele, so close follow-up of this patient population is indicated to promote prompt initiation when indicated.⁷⁹ The outcomes of the untethering procedure differ according to the type of presenting symptoms. The motor deficits and pain seem to improve in most of the patients, but the results are not as good for urological function. Postoperative long-term follow-up is mandatory, since symptoms of retethering will occur in up to 55% of patients.^{31,83,84} Release of a tethered cord can additionally stabilize or improve a progressive scoliosis in selected patients with myelomeningocele. Those presenting with curves $>40^\circ$ or thoracic neurological levels do not seem to improve in their curves after the untethering procedure and will ultimately require spinal fusion.^{85,86}

Latex allergy represents a major associated care issue in patients with myelomeningocele. It is an IgE-mediated reaction, which may range from mild symptoms of urticaria to severe intraoperative systemic anaphylaxis, and hence contributes to the increased risks of surgery in this patient population.⁸⁷ The prevalence of latex sensitization in patients with spina bifida, as determined by a latex skin test or an in vitro study for latex-specific IgE, has been reported to range from 25% to 51%, while clinical latex allergy had been found to be as high as 15–32%.^{88–92} A specific skin prick test for latex sensitivity appears superior to in vitro testing for latex allergy in terms of sensibility and specificity.⁹³ Age, number, types of surgical procedures (viz. urological and orthopedic nature) and the presence of a ventriculoperitoneal shunt seem to play an important role in the development of latex sensitization in children with myelomeningocele.^{88,90,91,93} It is, however, not clear whether the presence of atopy is a risk factor for latex sensitization development in children with spina bifida.^{88,90,92} The high prevalence of latex sensitization and allergy in patients with myelomeningocele justifies a primary prophylaxis by avoiding latex contacts, especially during anesthesia and surgery and also in daily life. Latex avoidance strategy has been demonstrated to be associated with safe surgical outcomes, even in patients with known clinical latex allergy.⁹⁴

Short stature is commonly encountered in spina bifida, affecting 43.5–60.5% of patients. It is more frequently noted in children with higher spinal lesions (the higher the level

of the meningocele, the greater the growth defect) and/or hydrocephalus.^{95–103} Multiple factors may be responsible for the observed short stature in patients with myelomeningocele.¹⁰¹ Lower limb contractures, spasticity and scoliosis may lead to disproportionate short stature. In addition, a significant proportion of these patients have growth hormone deficiency caused by structural brain defects or hydrocephalus.¹⁰⁴ Arm span measurement is a useful parameter in this setting. It can be easily obtained on or out of brace and is estimated to be an appropriate screening parameter together with serum insulin-like growth factor 1 and insulin-like growth factor binding protein-3 levels for the diagnosis of growth hormone deficiency in patients with myelomeningocele.^{95,103} Recombinant human growth hormone treatment has been reported to significantly increase near adult stature in growth hormone deficient children with myelomeningocele, without causing scoliosis progression. Relative obesity was also decreased with significant improvement of body mass index.¹⁰⁵ Early onset of puberty is another frequent finding.^{102,106,107} As growth hormone deficiency, this hormonal disorder seems to be of central origin and could be the consequence of damage to the hypothalamus or the pituitary gland due to increased intracranial pressure or increased mass of CSF.⁹⁹ Increased perinatal intracranial pressure has been demonstrated to strongly predict the occurrence of precocious puberty in both girls and boys with myelomeningocele.^{108,109} Treatment with gonadotropin-releasing hormone analogues can stop progression of pubertal development. Ideally, central precocious puberty in patients with spina bifida should be considered as early as possible to make possible early diagnosis and corresponding treatment.¹¹⁰ An incidence of cryptorchidism as high as 15% has also been found in male patients with myelomeningocele.¹⁰⁷

Prenatal Diagnosis and Fetal Surgery

Prenatal diagnosis has drastically affected the outcome of fetuses with myelomeningocele on many fronts. A prenatal diagnosis and formal antenatal consultations have led to the possibility of pregnancy termination, which has led to an overall decrease in the birth incidence. It also allows alterations in the mode of delivery (from vaginal to cesarean most of the times), change to earlier delivery (in cases with signs of progressive hydrocephalus), and now fetal surgical repair.¹¹¹

The usage of the different modalities available for neural tube defects prenatal detection varies worldwide

accordingly to the different national health policies and screening programs.^{112,113} Alpha fetoprotein (AFP) is a glycoprotein produced in the fetal liver, intestine and yolk sac. In embryos with an open neural tube defect and other non-neural tube lesion, the absence of the normal covering at the site of the defect allows large quantities of AFP to leak into the amniotic fluid and then into the maternal serum. The AFP serum test is performed between 15 and 22 weeks of gestation and its sensitivity ranges from 65% to 85%.¹¹³ When serum AFP is elevated, AFP amniocentesis and/or ultrasound are performed. Alpha fetoprotein amniocentesis has a non-negligible risk of complications, including miscarriage, and diagnostic accuracy can be significantly increased by amniotic fluid acetylcholinesterase determination.^{114,115} In some countries, the screening program for open neural tube defects relies only on high-quality ultrasonography.¹¹² The sensitivity of this modality has been reported to be as high as 100%.¹¹³ By defining lesion level, type, head circumference and the presence of associated anomalies, it can help predicting the postnatal outcome of affected fetuses.¹¹⁶⁻¹¹⁹ Fetal spine MRI is now used by many centers as the final noninvasive examination for prenatal evaluation of fetuses, with suspected myelomeningocele on ultrasound. Investigators reported its significant efficiency in terms of changing diagnosis, providing additional information, influencing prenatal management and predicting adverse postnatal outcomes.¹²⁰⁻¹²³

Myelomeningocele was the first nonlethal congenital anomaly to be treated with fetal surgical repair, with the first case being operated by hysterotomy in 1997.¹²⁴ The rationale for fetal surgery for myelomeningocele arose from human ultrasound observational studies and animal models of myelomeningocele with intrauterine repair, supporting the evidence that secondary neurological deficit may arise from chronic chemical and mechanical insults of the neural tissue by exposure to amniotic fluid.¹²⁵⁻¹²⁷ Both fetoscopic and open methods have been described, but open techniques seem to represent the current standard.¹¹¹ A randomized trial comparing prenatal repair before 26 weeks of gestation versus standard postnatal care recently demonstrated the benefits of fetal surgery for myelomeningocele, reducing brain stem herniation and the need for shunting, and improving motor and psychomotor outcomes at 30 months. However, the procedure was associated with maternal and fetal risks, including an increased risk of preterm delivery and uterine dehiscence at delivery.¹²⁸ The majority of children treated with fetal repair for myelomeningocele will achieve at preschool age cognitive and mobility independence, but they will

continue to necessitate significant assistance in self-care.¹²⁹ Unfortunately, neurogenic bowel and bladder management remains an important issue for patients, even after fetal myelomeningocele repair, so that they should be followed closely, similar to patients with myelomeningocele who undergo standard postnatal care.¹³⁰

Postnatal Management

Importance of Multidisciplinary Approach

Myelomeningocele is one of the most complex birth defects, affecting multiple body systems and secondarily function. This complexity needs involvement of multiple disciplines in order to deliver improved and integrated health care to patients with spina bifida. The involved specialists should include providers with expertise in the fields of neurosurgery, orthopedics, urology, general pediatrics, developmental pediatrics, physiatry, and nursing. Patients with myelomeningocele additionally often benefit from other related health care services, including nutrition, social work, physical therapy, occupational therapy (wheelchair, bracing, or seating), psychology, and family support services.^{131,132} The development of multidisciplinary clinics and teams in the 1960s was the answer to the recognition of these challenges of providing health care to children with myelomeningocele. The multidisciplinary clinic still represents today the accepted model of health care delivery to these patients.¹³³ Disbanding a multidisciplinary clinic was reported to negatively impact health care of patients with myelomeningocele, with less frequent care, loss of a coordinator of care, and a significant increase in morbidity, including amputation and nephrectomy, despite the continued availability of the same specialty care in the same location.¹³⁴ With the improvements in medical and surgical management of myelomeningocele, >75% of patients can be expected to reach their adult years. Late deterioration is frequent and rates remain lower than expected for community participation, healthy lifestyle choices, and employment and independent living. One of the current challenges is to adequately manage the adolescent with spina bifida through transition to adulthood and to promote the transfer of care to a network of adult care clinics.^{89,135}

Guiding Principle of Management of Myelomeningocele Spinal Deformities

Management of myelomeningocele spinal deformities must take into consideration each patient's individual limita-

tions, his or her expectations and his or her comorbid conditions. The location of the myelomeningocele and the resulting functional levels will dictate and significantly influence the types of treatments required to manage the spinal deformities. In addition, the underlying nature of the spinal deformity, such as congenital hemivertebra, or hyperlordosis due to a split tether cord, or even kyphoscoliosis from a simple loss of erector strength, must be identified at the onset of the treatment. All these factors will influence and dictate the nonoperative and operative treatment.

Closure of the Myelomeningocele

The initial surgical management is a critical step in the treatment of myelomeningocele and involves early closure after birth. Essential goals of surgery are preservation of neurological function, prevention of infection and avoidance of surgical complications. The discovery of a myelomeningocele is usually unexpected and careful explanation of the disease and the aim of the early treatment have to be rapidly explained to parents in order to carry out surgical treatment. Repair of the myelomeningocele involves different pre-, intra- and postoperative considerations that are equally important for surgical success.¹³⁶⁻¹³⁸ As myelomeningoceles are always associated with a Chiari II malformation, it is important to obtain a brain MRI before surgery to assess the degree of tonsillar descent and compression of the bulb and severity of hydrocephalus, which may require shunting after closure of the myelomeningocele. The difficulty of surgery and neurological prognosis depends of the anatomical variant and localization of the myelomeningocele along the neural tube.¹³⁹

Preoperative considerations: Special care has to be provided to the placode, which should be covered with humid sterile gauze to prevent desiccation and provide mechanical protection. The child should be nursed in a prone position to prevent further mechanical injury to the placode. At the time of surgery, the child is anesthetized by dedicated pediatric anesthesiologist and placed in a prone position with special care to avoid pressure point, and the placode is slightly elevated from the head to avoid continuous CSF loss. Electrophysiological monitoring even at this age is a useful tool to assess nerve root function during surgery. Microinstruments and surgical microscope are needed for use in theater. Prepping and draping are done carefully around the deformation. Skin incision is made at the junction of the normal and abnormal thin skin, allowing the development of a dissection plane between the placode

and the surrounding tissue. Extra care has to be taken to preserve vascular supply to the placode to ensure survival of the neural tissue. The free edges of the dura are exposed all around the deformation and can be held open for later reconstruction of the neural tube. An important aspect during surgery is to avoid repetitive traction on the cord, thus limiting the risk of subsequent neurological injury. Often below the placode, a thickened filum can be seen and needs to be divided. Also, all tethering bands around the placode must be freed.

An important step of the surgery is the anatomical reconstruction, which has to be done plane by plane. Usually, the malformation involves an open-ending neural tube with a central canal surrounded by the free edges of the neural tissue. One of the more critical steps of the procedure is the reconstruction of the neural canal by folding the neural placode along its long axis and held in place with a pial-to-pial closure, which is illustrated in Figure 22.1. Conceptually, this should prevent the risk of retethering. Gentle traction to the suture is critical to prevent risk of neural compression and postoperative neurological deficits. The dura is then closed with a watertight continuous running suture, once the lateral dural attachments have been freed from surrounding subcutaneous tissue (Figs. 22.2A to F). Closure of the fascia is not always achievable due to the wide opening of the spinal canal and lateral borders of the paraspinal muscles, but attempts should be made to dissect the surrounding fascia from overlying skin to obtain as much tissue for closure. Some techniques include more extensive muscle and fascial flap closure.¹⁴⁰ For skin closure, release and dissection of the subcutaneous tissue around the opening is critical to obtain as much mobile skin to close the subcutaneous tissue with 3.0 Vicryl stitches and the skin with a single suture or a running rapid 5.0 Vicryl suture. A dry dressing is used and covers the lower part with a transparent adhesive dressing just at the upper part of the sacral rim to prevent fecal contamination. The patients are nursed in a strict prone position for at least 48 hours to ensure initial healing of the wound and prevent CSF leak. Close follow-up is recommended to ensure the wounds are healing well. Moreover, these children need regular multidisciplinary follow-up.

Orthotic Treatment of Ensuing Spinal Deformities

The nonoperative management of myelomeningocele spinal deformities should be focused on function rather than on prevention of deformity progression. The loca-

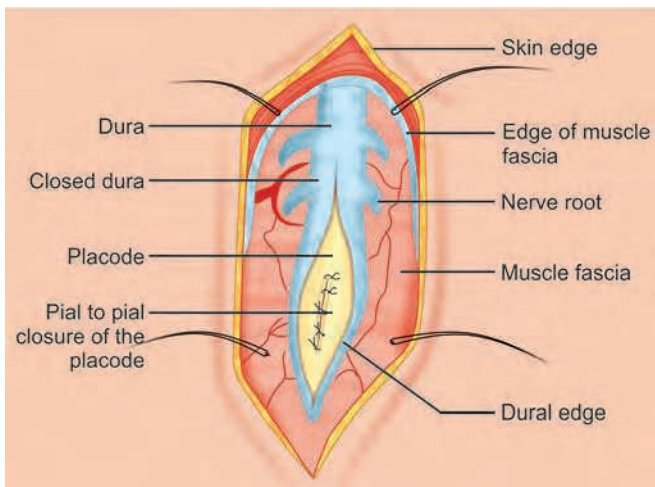


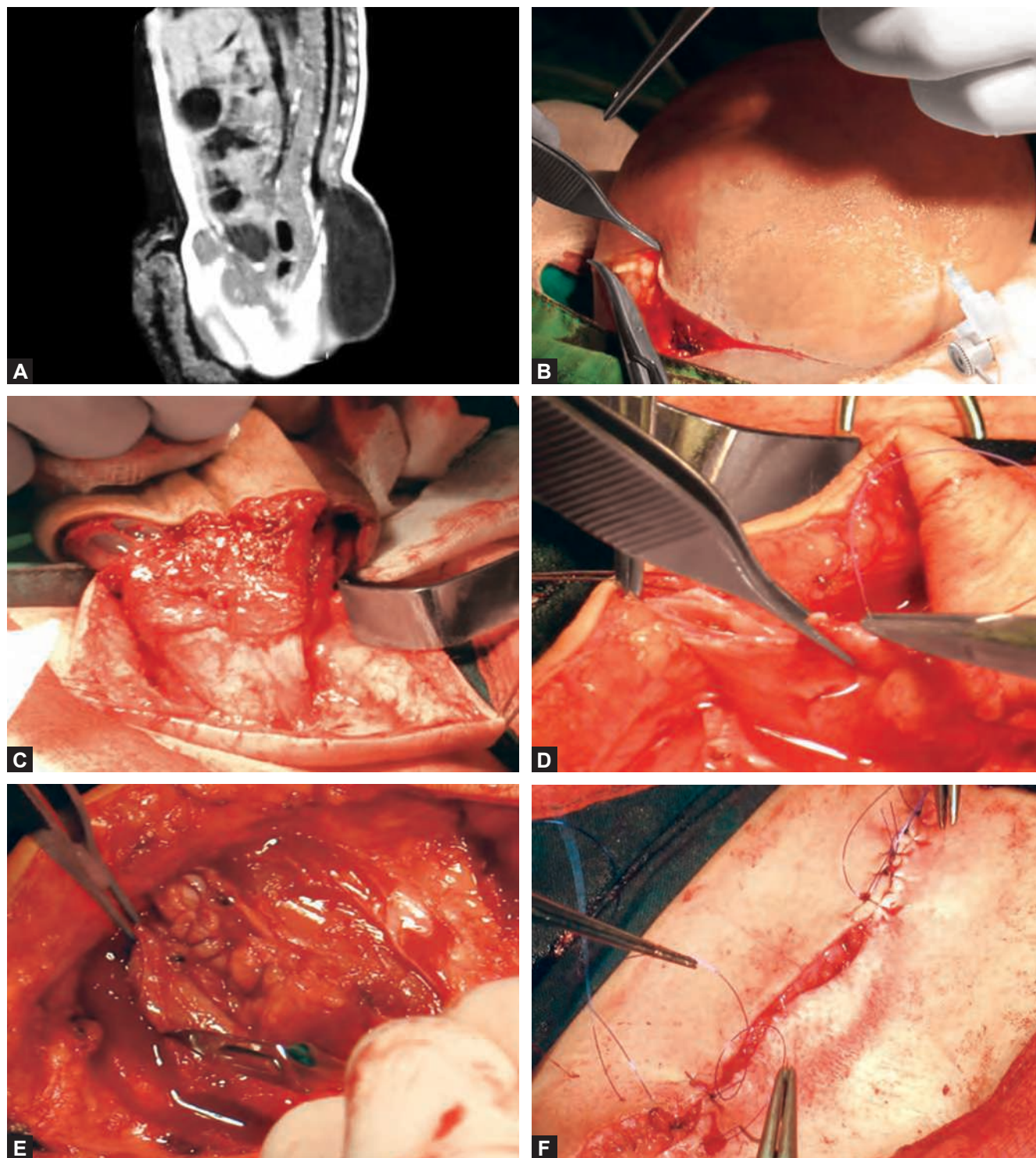
Fig. 22.1: Schematic representation of a surgical view: The placode is closed with a pial to pial dissection. Adhesion between the pia and the dura need to be released to reduce the risk of retethering. The dura is closed with a watertight suture. The fascial plane on each side is released with a subcutaneous dissection to obtain enough tissue for closure.

tion of the myelomeningocele and the resulting functional levels as well as the nature of the deformity will dictate the types of treatments required to manage the spinal deformities. A congenital kyphoscoliosis associated with T11 myelomeningocele will not be managed the same as a sacral myelomeningocele presenting with a thoracic curve. Hence, in the absence of any failure of formation or segmentation of the vertebra, a low lumbar and lumbosacral myelomeningocele presenting with a thoracic or lumbar curve is treated essentially as idiopathic scoliosis with classic bracing indications. However, in the presence of a structural congenital oblique takeoff at the lumbosacral junction, leading to the idiopathic-like lumbar curve may require a hemi resection of the offending vertebra (Case 1). In patients with high lumbar myelomeningocele who are still able to be upright, treatment can consist of spinal bracing if it allows prolongation of an upright position while maintaining standing/ambulation status. Once patients are wheelchair-dependent, then seating modifications are warranted to provide lateral trunk support, as well as accommodation of any sagittal deformities such as hyperlordosis or kyphosis. For thoracic level, myelomeningocele in patients with muscle hypotonia and important thoracolumbar/lumbar curves measuring $>40^\circ$ as well as in nonambulating patients with spastic large lumbar curve, bracing is considered purely as functional bracing, as it has not been shown to alter the progressive nature of the

neuromuscular scoliosis. It can be used as sitting support.¹⁴¹ Bracing provides an external support to the spine, allowing some patients to be more functional. Its goal is to maximize functional positioning by controlling some of the spinal collapse, improving posture, and may facilitate seating. One must be vigilant as to possible worsening pulmonary function in patients with high myelomeningocele. In addition, particularly with high-level myelomeningocele, the insensate skin is at risk of breakdown and ulcers. Seating modification and choice of surface must be carefully chosen to minimize skin breakdown while providing enough support to minimize and control pelvic obliquity. Controlling and compensating hip contractures must also be taken into consideration to favorably influence the pelvis to minimize an oblique take off of the spine.

Surgical Management

Surgical management of spinal deformities in patients with myelomeningocele carries elevated morbidity and mortality rates. Common surgical complications in this patient population are deep wound infection, osteomyelitis, skin ulceration resulting from recurrent deformity or prominent implants, CSF flow dysfunction requiring shunt revision, and death. Thorough pre- and perioperative management with a multidisciplinary team approach has led to successful surgical outcome, with most patients and caregivers feeling that their spinal surgeries were beneficial to their overall well-being.^{3,142} The surgical indications for corrective spinal deformity in patients with myelomeningocele remain contentious.¹⁴² The decision to proceed with surgery must not be taken lightly in light of the overall complication rate. Severe spinal imbalance, pressure sores and loss of function¹⁴³ are the common indications to proceed with surgical management in this patient population. As their spinal deformities progress, they often decompensate in both the coronal plane and the sagittal plane, leading to significant spinal imbalance. Pronounced spinal imbalance may ultimately lead to inability to walk in the ambulatory patient, while in the wheelchair-dependent patient, it may lead to deterioration of sitting comfort and loss of sitting independence, ultimately leading to loss of activities of daily living and decrease in quality of life. Furthermore, such trunk shift and spinal imbalance can be the cause of ischial or sacral pressure sores, particularly when there is associated pelvic obliquity. These sores are indications to proceed to corrective surgeries (Case 2). The type of loss of function these

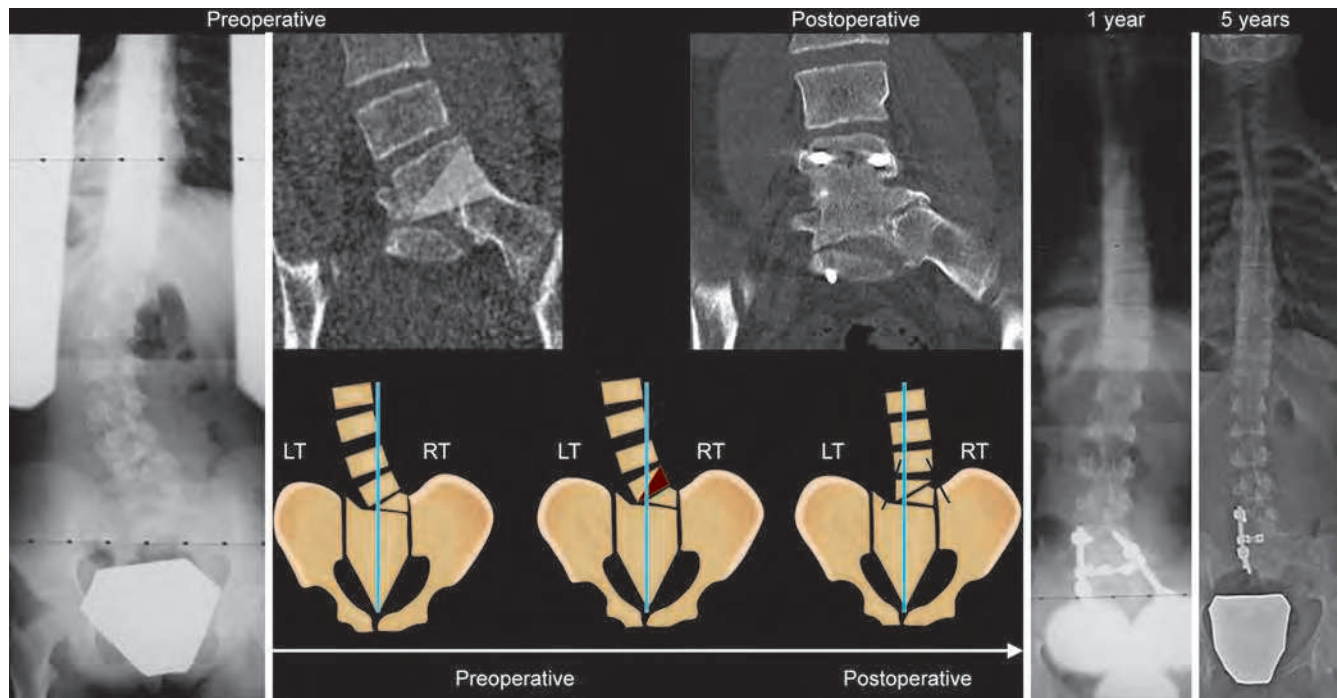


Figs. 22.2A to F: Closure of a sacral myelomeningocele (A) preoperative MRI showing the sac of the myelomeningocele and its continuity with the neural tube; (B) epileptoid-shaped skin opening finding the subcutaneous plane with the myelomeningocele sac; (C) dissection around the neck of the myelomeningocele sac, showing the dural plane with the surrounding muscle fascia; (D) the sac is open, and the dura containing the end of the placode is closed with a watertight suture; (E) the fascia is dissected to obtain a layer on both sides that can be closed; (F) the skin is closed with single stitches or a running suture.

Source: Photographs by Dr Benedict Rilliet.

CASE 1

An 11-year-old girl presents with a progressive lumbar curve. Investigation reveals a spina bifida occulta of S2 and a hemivertebra of S1. Corrective surgery consisted of partial resection of L5 rather than S1 hemivertebra via anterior and posterior approach and fusion and instrumentation L4–pelvis. Eventual partial hardware removal second to pain. Last follow-up, patient was asymptomatic 5 years postoperatively.



patients experience can be subtle. For example, patients with a thoracic myelomeningocele and spinal imbalance typically end up supporting themselves with one of their hands, resulting in a function triplegia. Paralytic kyphotic deformities in these patients are by themselves surgical indications, as these are progressive to the rate of 4–13° per year and are resistant to all forms of conservative treatment. One last consideration for surgical management of the patients with myelomeningocele with spinal deformities is when their wheelchair can no longer be adapted to compensate for their spinal imbalance and/or their deformity.¹⁴⁴

Goals of Surgery

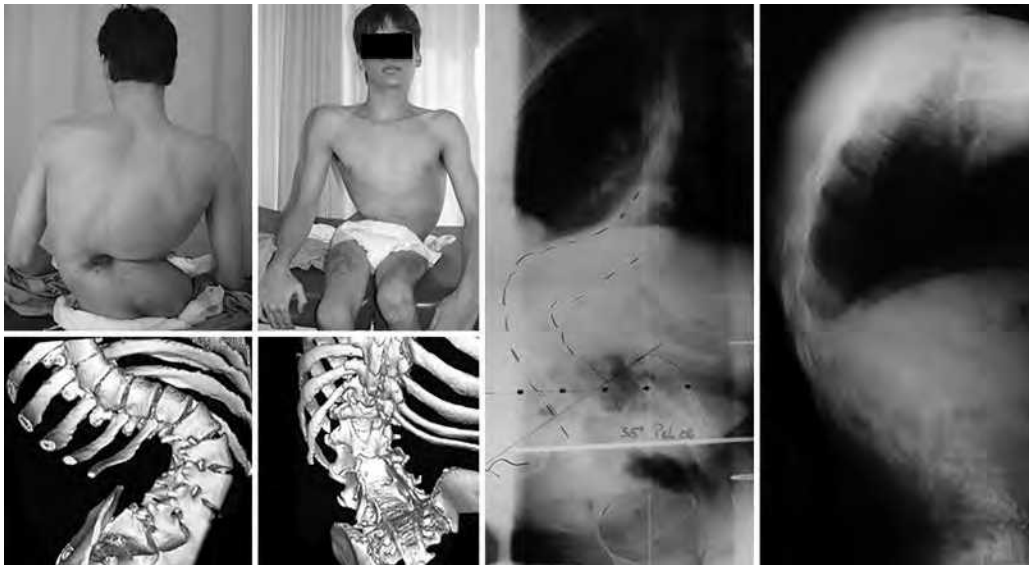
In all spinal deformity correction surgeries, the primary goal is to achieve spinal balance both in the coronal plane and the sagittal plane¹⁴⁵ with the least amount of risk. This cannot be overly emphasized in patients with myelomeningocele, as they classically do not have compensatory

mechanisms such as muscle tone and/or intact proprioception to rebalance themselves. Achieving balance redistributes their weight and conceptually minimizes their risk of pressure sores in both planes: Coronal imbalance 146 (Case 2) or sagittal imbalances (Case 5). It has been shown that kyphectomies Improves Sitting and Skin Problems in Patients with Myelomeningocele.”¹⁴⁶

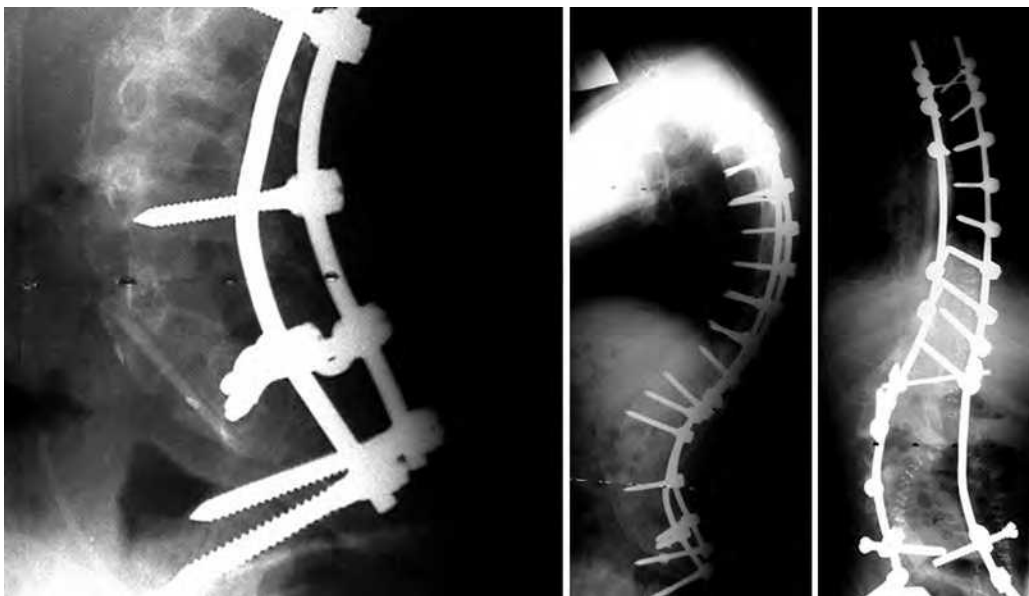
The second objective of the surgery, which is particularly challenging in this patient population, is to achieve a solid fusion.¹⁴⁷ Achieving this solid fusion is crucial, as about half of patients with myelomeningocele with posterior spinal fusion¹⁴⁸ run the risk of developing a deep posterior spinal infection¹⁴⁹⁻¹⁵¹ with the possible necessity of hardware removal. By lacking posterior bony elements, the classic posterior lateral bone grafting technique is often inadequate. To achieve a lifelong solid fusion, it is recommended to undertake either a formal anterior approach and fusion across the segment of spinal dysraphism (Figs. 22.3A to E) or via a posterior approach, an intervertebral bone grafting technique across

CASE 2

A 16-year-old male nonambulatory with an L1 myelomeningocele, struggling for one year with a left ischial chronic skin ulcer. Patient has a severe spinopelvic deformity consisting of 100° scoliosis with 30° of pelvic obliquity compounded with hyperlumbar lordosis with thoracic kyphosis.



Patient underwent anterior thoracolumbar release, anterior interbody fusion T12 to S1 across the spinal dysraphism. Due to the hyperlordosis, the L5-S1 disc space was accessed via the body of L5 and a tibial strut graft was impacted across the disc space. Patient then had a posterior spinal instrumentation and fusion from T3 to pelvis with maximum width (MW) fixation correcting the pelvic obliquity. Across the thoracic spine, multiple Smith Peterson osteotomies were done to partially correct the thoracic kyphosis. Due to the poor midline skin, an U-shaped skin incision was done avoiding the dysraphism. (see the skin staples on postoperative film).

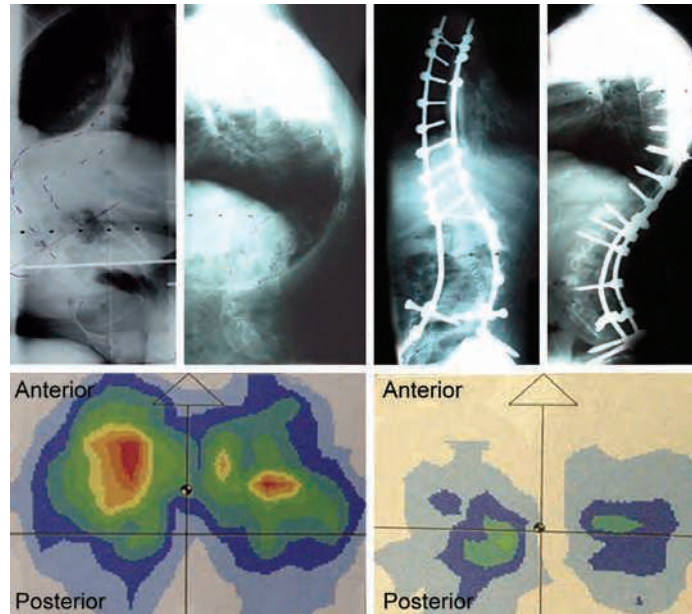


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CASE 2

Preoperative pressure mapping shows asymmetrical weight distribution secondary to pelvic obliquity and spinal imbalance in both planes. Postoperative X-rays and pressure mapping confirm spinal balance in both coronal and sagittal planes after correction.



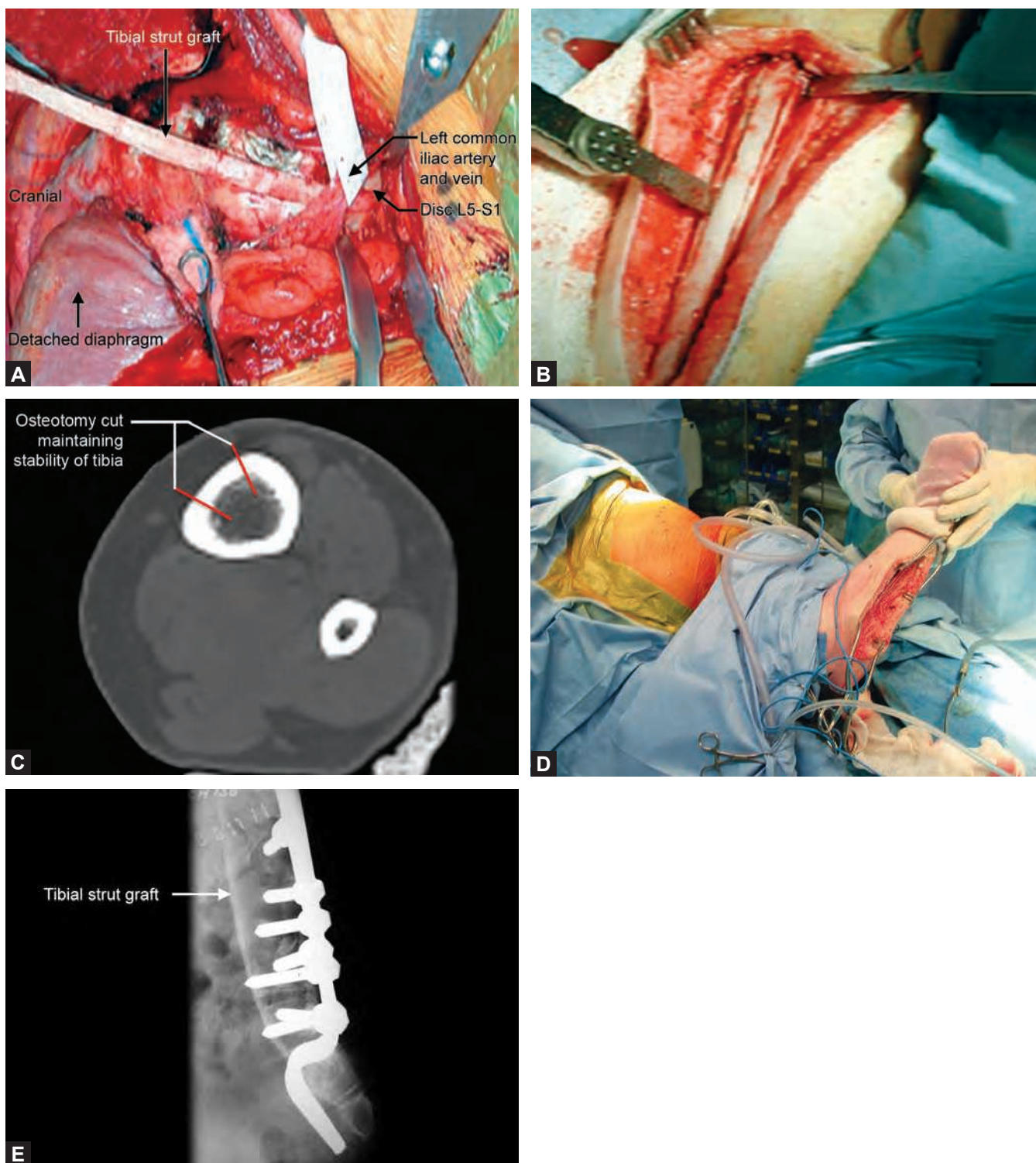
the spinal dysraphism [posterior lumbar interbody fusion (PLIF), transforaminal lumbar interbody fusion (TLIF)].¹⁵² Ligation and transection of the spinal cord and the thecal sac below the functional level of the spinal dysraphism provides great access to the anterior spinal column. Of note, such transection has been associated with altered CSF flow leading to hydrocephalus, as well as altered bladder function.¹⁵³ Patient with neurogenic bladders can remain dry as long as their urethral sphincter remains spastic/closed. Some patients who have had undergone transection of their spinal cord lose tone in their sphincter, rendering them constantly wet, which is a major problem for perineal care and hygiene. In addition, transection of the cord and ligation of the sac are associated with significant blood loss.¹ Instead of transecting the cord and ligating the dural sac, the sac can be mobilized by ligating and cutting the exiting nerve roots and retracting the dural sac on either side, providing access to the anterior column of the spine. From a biological point of view, anterior bone grafting is thought to be superior¹⁵⁴ as it remains under compression load, which stimulates bone healing, while posterior bone grafting is thought to be under tension and can remodel and even resorb.

Preoperative Workup

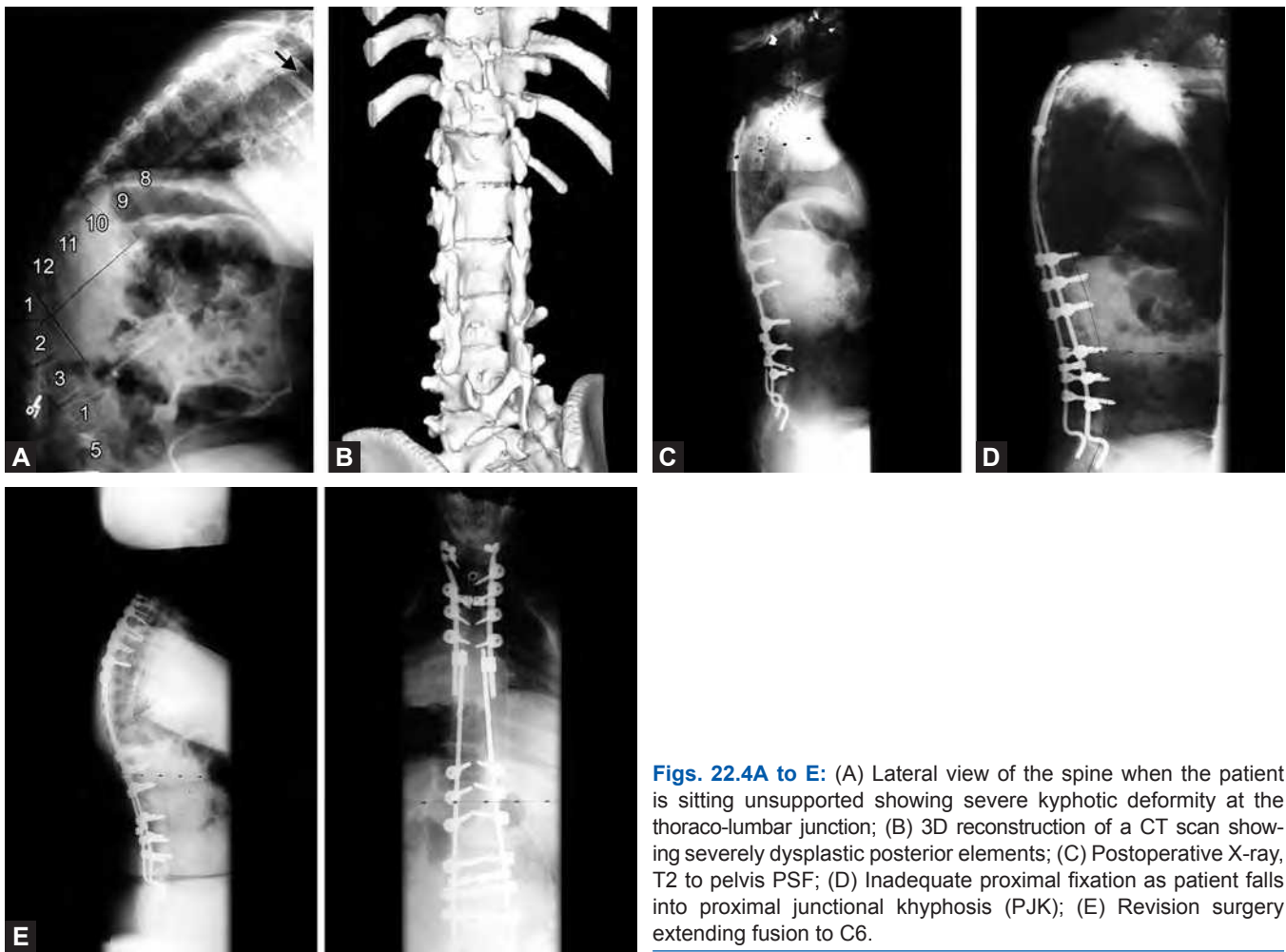
During the preoperative workup, patients' nutritional status must be assessed and optimized. Total protein, low hematocrit < 33 and albumin count can provide a clue to the patient's nutritional status.³ If deficient, then patient should be placed on nutritional supplements. As previously described, patients with myelomeningocele run a higher risk of having central apnea second to basal skull pathologies and need to be assessed for this. They often have colonization of their urinary tracts, hence these patients should receive antibiotics that covers gram negative organisms in addition to prophylactic antibiotic coverage for skin flora to minimize deep wound infections.³

Levels of Fusions

Choosing fusion levels in patients with myelomeningocele is relatively straightforward. Having no specific curves pattern dictating alternative fusion levels, one can rely on Harrington basic concept—fuse the Cobb angle, i.e. end vertebrae to end vertebrae. However, this being said,



Figs. 22.3A to E: (A) Anterior thoracoabdominal approach with diaphragm detached and mobilization of the common iliac vein and artery (Penrose) allowing for impaction of tibial autograft across the thoracolumbar and lumbosacral junctions; (B) Harvest of tibial strut graft; (C) Care must be taken to leave the "corners" of the triangular shape tibia to avoid postoperative tibial fracture; (D) Draping allowing harvesting to occur at same time of thoracoabdominal approach. (E) Postoperative X-ray showing tibial strut graft impacted in S1 up to T11.



Figs. 22.4A to E: (A) Lateral view of the spine when the patient is sitting unsupported showing severe kyphotic deformity at the thoraco-lumbar junction; (B) 3D reconstruction of a CT scan showing severely dysplastic posterior elements; (C) Postoperative X-ray, T2 to pelvis PSF; (D) Inadequate proximal fixation as patient falls into proximal junctional kyphosis (PJK); (E) Revision surgery extending fusion to C6.

in general, they tend to require additional levels of fusion as they have associated sagittal deformities such as global kyphosis and/or pelvic obliquity,¹⁵⁵ resulting in a classic neuromuscular T2 to pelvis fusion.^{4,156} Patient with pelvic obliquities $>15^\circ$ should have their fusion extended to the pelvis.¹⁵⁷ Of note, in the presence of kyphotic deformities, it is crucial that there are adequate anchor points proximal and distal to the apex of the deformity due to their poor bone quality secondary to disuse osteopenia or prolonged antiepileptic use. This poor bone quality places the implants at high risk of pullout.¹⁵⁸ Ideally, the proximal instrumented vertebra should be at the level of the first lordotic spinal segments on the lateral (Figs. 22.4A to E) above the kyphotic deformity. Selective spinal fusion¹⁵⁹ should be discouraged in this patient population, as it runs an additional risk that the nonfused segments may develop new deformities such as junctional kyphosis, particularly in the patients with hypotonic myelomeningocele. Fusing

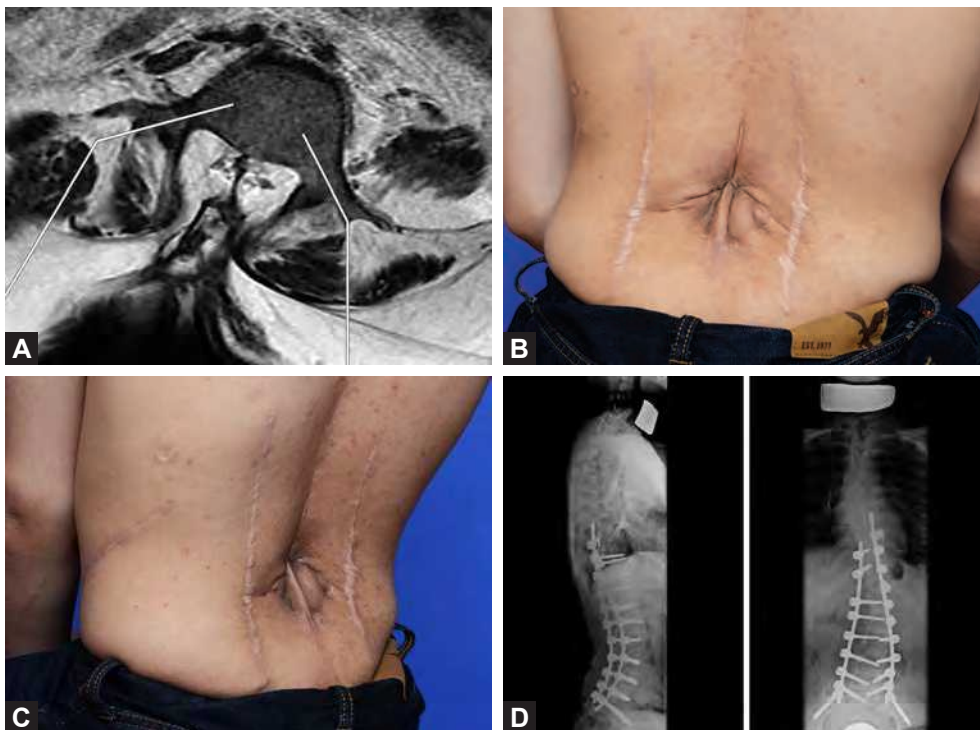
long will avoid problematic revision surgery addressing junctional kyphosis or progressive pelvic obliquity; however, long fusion may lead to loss of function. For certain patients, their spinal deformities are actually beneficial to them. For some, having a collapsing spine lowers their center of gravity, facilitating their sitting balance. For others, having a shortened trunk facilitates their access to their perineal area for self-catheterization. In addition, a shortened spinal height can be beneficial, as their shoulders are closer to the ground and to the wheels of their wheelchair, facilitating their lifts and transfers as well as improves the power they can generate in a sitting position.¹⁶⁰ Patients' level of activity can influence the choice of fusion levels.¹⁶¹ Patients involved in paraolympic sports¹⁶² requiring thoracic motion may opt to have shorter fusion and assume the risk of requiring further surgeries to address the ensuing deformity at a later date (Case 3). The choice of fusion levels must be taken in consideration with all these factors,

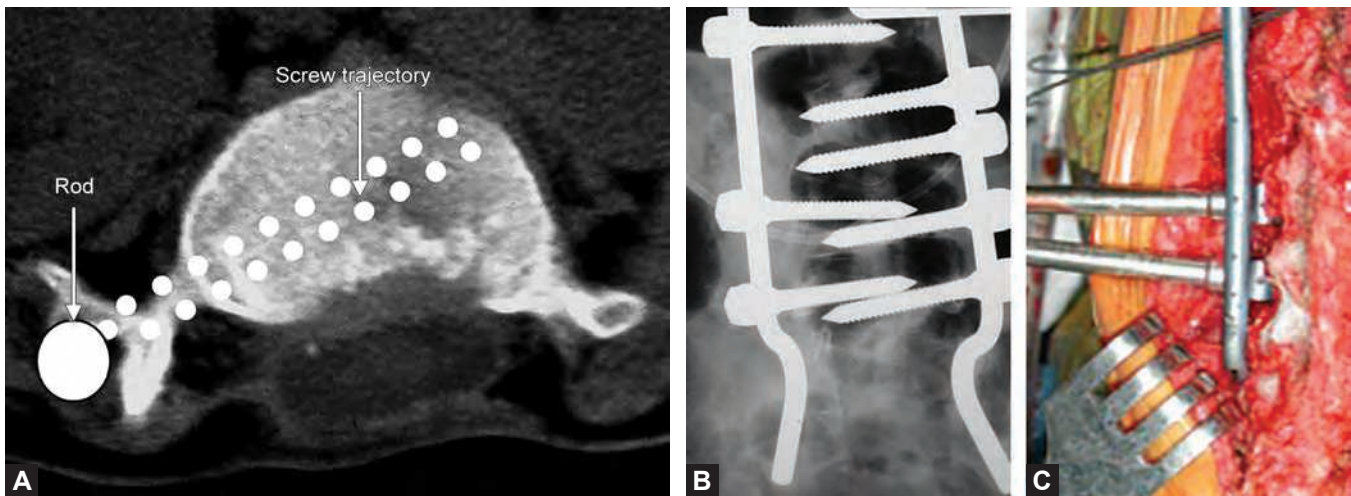
CASE 3

A 15-year-old boy on state para-basketball team, L1 myelomeningocele with progressive lumbar scoliosis with problematic pelvic obliquity. Patient has normal sagittal balance, good trunk control, minimal compensatory thoracic curve.



Patient undergoes a selective lumbar fusion with extension to pelvis via paramedial incisions avoiding the midline skin breakdown and risk of CSF leaks. Three months later, he undergoes formal anterior thoracolumbar spinal fusion across all segments. Patient is now 3 years postoperative and continues to play college-level and Olympic basketball.





Figs. 22.5A to C: Modified Pedicle-vertebral body screws. (A) The entry point is at the base of the residual transverse process and needs to be significantly convergent; (B) The orientation of the screws resembles much more an anterior vertebral body screw. Right and left pedicle screws need to be slightly staggered proximal to distal, thus avoiding the opposite screw; (C) Such pedicle screw orientation allows rod positioning very lateral, hence minimizing prominence of spinal implants.

which are typically not found on X-rays. A frank discussion needs to occur with the patients and their families as to their expectation.¹⁶³ When a long fusion is undertaken, correction must lead to coronal and sagittal balance, with normalization of the sagittal alignment but moderating the urge to overcorrect the kyphosis.

Types of Spinal Fixation

The classic spinal implants for the instrumentation of the neuromuscular curves comprise sublaminar wires and L-rods.¹⁶⁴ Sublaminar wires are still being used¹⁶⁵ and remain advantageous for different reasons: minimal cost, low profile and good fixation in osteoporotic bone. Across the spinal dysraphism, as there are no laminae, the wires are passed from one foramen to the other, creating a cerclage around the pedicle stump. The overlying facets prevent the cerclage from dislodging, providing a good spinal anchor. The disadvantages of wires are the potential risk of injuring the intact neural elements (if any), tearing the dural sac during insertion, and risk of considerable epidural bleeding.¹⁶⁶ Great care must be taken as to the final placement of the twisted wires, as they may pierce the overlying skin leading to deep infections. Their tips should be twisted and tuck away under the rod or impacted into the adjacent bone. The advent of modern spinal fixation, such as pedicle screws has improved spinal stabilization for corrective surgery in neuromuscular scoliosis.¹⁶⁷ Insertion and place-

ment of “pedicle” screws in patients with myelomeningocele are obviously different than the standard pedicle screws. The main difference is the entry point, and the orientation of the residual pedicle stump is much more lateral and much more convergent. The entry point is at the base of the residual transverse process and needs to be significantly convergent. The screw heads need to be buried to avoid skin breakdown. The orientation of the screws resembles much more an anterior vertebral body screw than a pedicle screw, as the screws come across the vertebra almost in a pure coronal plane. When a right and a left pedicle screws are inserted, the entry points need to be slightly staggered proximal to distal, thus avoiding the opposite screw (Figs. 22.5A to C).

Sacral and Pelvic Fixation

Pelvic fixation¹⁶⁸ in the patient with myelomeningocele can be problematic.¹⁶⁹ Their pelvis tends to be osteoporotic and may be asymmetrically hypoplastic altering the normal anatomy. The classic spinopelvic fixation to manage pelvic obliquity associated with neuromuscular scoliosis has been the Luque-Galveston construct.^{169,170} This pelvic fixation consists of inserting the distal rods between the inner and outer tables at the level of the posterior superior iliac spine all the way across to the anterior superior iliac spine (ASIS) just above the sciatic notch. The rods need to be bent in different planes to match the lumbopelvic junction.

Additional stability of the construct can be obtained by coupling both rods with a cross link at the level of L5 and inserting bilateral S1 pedicle screws.¹⁷¹ The Unit Rod,¹⁷² a prebent U-shaped single rod, has also been shown to be an effective means of correcting the pelvic obliquity and the spinal deformity.¹⁵¹ A natural evolution of the Galveston technique was to replace the smooth rod with an iliac screw, diminishing the inherent complication of pull out and/or windshield loosening. To achieve a heightened accuracy of placement of these iliac screws, a dissection along the external table of the iliac wing can be done to establish where the sciatic notch is located using a blunt probe. Staying subperiosteal is crucial to minimize but does not exclude the risk of injuring the superior gluteal artery located in the notch.¹⁶⁷ The other technique described to improve screw placement is the use of fluoroscopic imaging. The gantry of the C-arm is oriented in the long axis of the iliac wing, creating a tear-drop-like picture allowing to confirm the ideal placement of the iliac screws.

Dunn and McCarthy described in 1989, a sacropelvic fixation specifically but not limited for patient with myelomeningocele. The S-rod fixations are prebent rods placed over the sacral ala between the transverse processes of L5 and the ileum. The S-shape portion of the rod needs to be well seated on the ala and firmly abutted anterior to the sacrum. This can be achieved by applying distraction on the rod with an L5 pedicle screw or laminar hooks. Having the rods anterior to the sacral ala and sacrum provided an added lever arm and strength to the sacropelvic fixation particularly when correcting lumbar kyphosis. Such fixation is best for the nonambulating patients with myelomeningocele, as the L5 nerve root is at risk of compression as it rests on the sacral ala. In addition, seeing the Dunn McCarthy rods are anterior to the sacrum and sacral alas, one is able to exert significant corrective force without relying on an osteoporotic pelvis.

For severe pelvic obliquity, a maximal width, “MW” segmental type of sacropelvic fixation has also been described and shown to be effective. “MW” pelvic fixation comprises a pedicle screw inserted in a Galveston fashion down the iliac wing 1 cm above the sciatic notch. As an added lever arm to correct the pelvis, a sublaminar hook pushes or pulls on an iliosacral screw described by Dubousset.

Recently, Sponseller described a sacral alar iliac screw where the entry point for this pelvic fixation lies on the sacrum, just inferior-lateral to the dorsal S1 foramen. Its trajectory is approximately 40° of lateral angulation in

the transverse plane and 40° of caudal angulation in the sagittal plane. The screw crosses the SI joint to then travel between the inner and outer tables of the iliac. The length of these screws typically ranges from 70 to 100 mm with a diameter from 7.5 to 10 mm. The advantage of such pelvic fixation is that it potentially minimizes implant prominence when compared with other fixation techniques.¹⁷³ Independent of the technique used, great care must be taken to avoid any prominent implants, as patients with myelomeningocele are excessively prone to skin breakdown due to inexistent muscle mass and insensate skin. The other challenge to manage pelvic obliquity¹⁶⁹ in this patient population is the surgeon’s ability to assess intraoperatively, if the pelvis has been leveled. Are the ischia at 90° to the spine? In certain cases, having the pelvis at 90° still does not result in balanced spine because of infrapelvic or intrapelvic asymmetry leading to uneven sitting. The advantage of using the unit rod is that if inserted correctly in the pelvis, then once the cantilever maneuver done, the pelvis has to be corrected 90° to the spine. The disadvantage is that once inserted and the correction done, if the pelvis is not 90° to the spine, then there is no segmental adjustment to be done. The advantage of the use of segmental fixation with iliac screws is that the insertion is easier; coupling to the spinal rod can be done after the iliac fixation is done and can theoretically be adjusted to attempt to obtain further correction. The downside is that seeing the coupling of the pelvic fixation to the spine fixation is not fixed at 90°, then the risk is that after the cantilever maneuver, the pelvis is still not leveled. A good technical reference for pelvic fixation is the article that Dayer et al. published in *Curr Rev Musculoskelet Med*. 2012 (Fig. 22.6).¹⁶⁸

The classic reduction maneuver for correcting pelvic obliquity consists of a cantilever maneuver¹⁷⁴ (Fig. 22.7). This entails fixing the rods distally to the pelvis at a 90° orientation to the ischial tuberosities. Then, the rods are levered across and attached to the proximal spine, thus leveling the pelvis perpendicular to the balance of the spine. Entry point in the posterior superior iliac spine (PSIS) are crucial for the unit rod and Galveston techniques as this will determine, if the pelvis will be leveled after the reduction maneuver (Fig. 22.6).

Anterior Surgery

Under certain circumstances, it may be beneficial to undertake single anterior spinal instrumentation and fusion

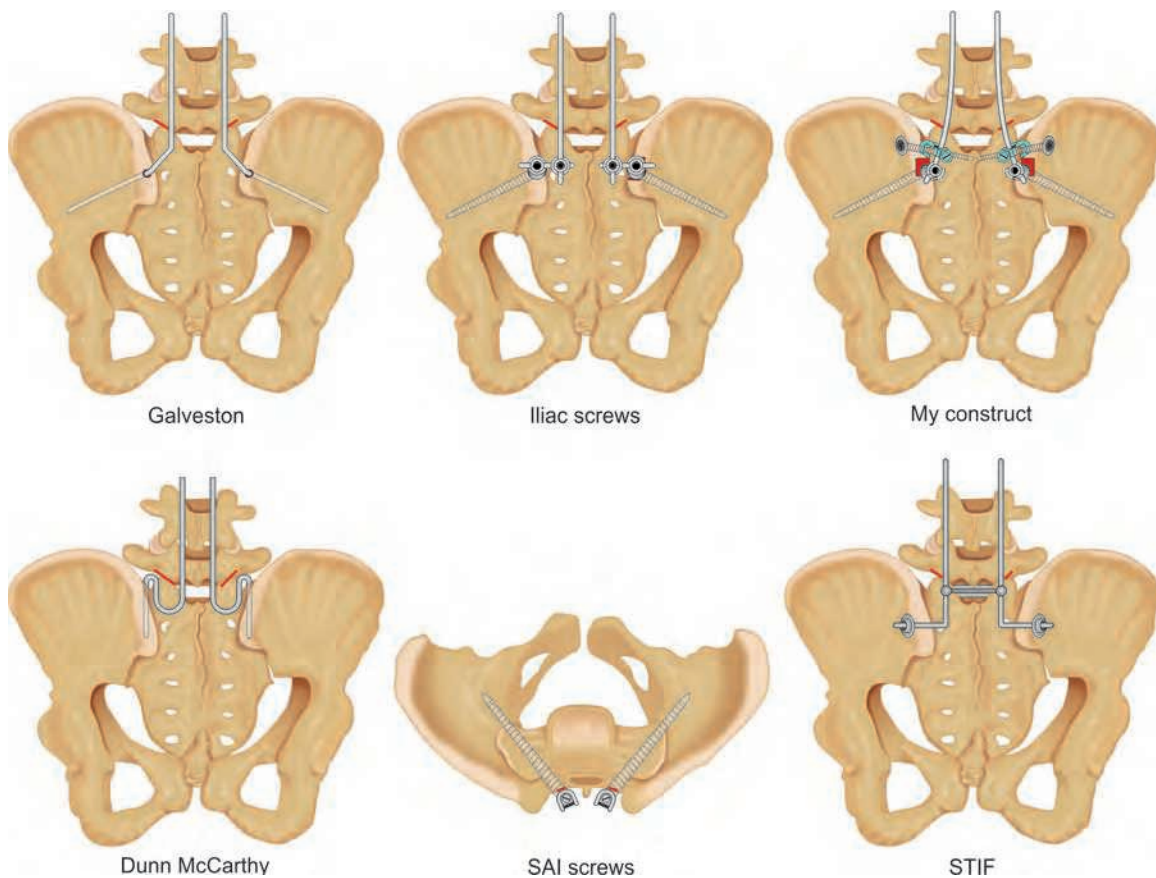


Fig. 22.6: Types of pelvic fixations.

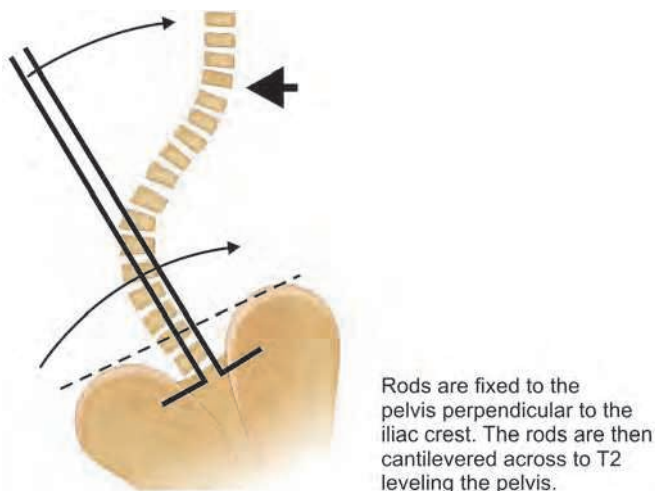


Fig. 22.7: Rods are fixed to the pelvis perpendicular to the iliac crest. The rods are then cantilevered across to T2 leveling the pelvis.

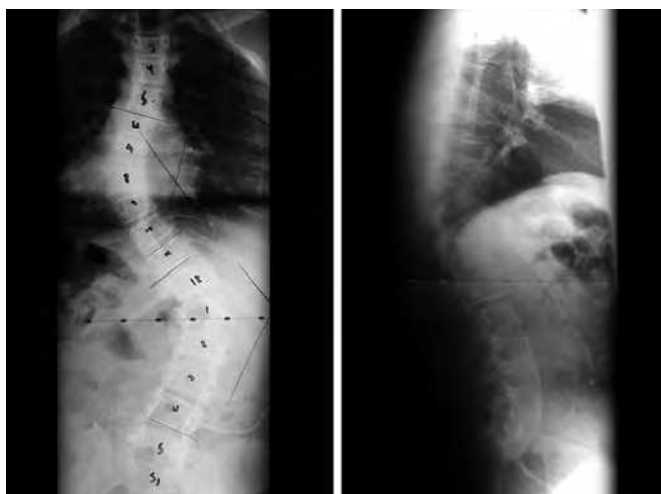
in the patient with myelomeningocele. Sponseller et al recommended that in the patient with poor skin coverage and/or chronically infected posterior draining wound with

relatively supple lumbar/thoracolumbar curves $< 75^\circ$ with no kyphosis or no need to extend the fusions down to the pelvis, single anterior spinal fusion should be undertaken (Case 4).¹⁷¹ Patients with severe kyphotic deformities requiring significant corrections should also undergo anterior surgery, ideally with insertion of structural bone grafting (tibia or ribs) preventing the deformity from recurring.¹⁷⁵

When combined anterior and posterior surgery is required, the controversy continues regarding the ideal timing of the surgeries: same day versus staged.¹⁷² If staged,¹⁷⁶ how long between the two surgeries should one wait. One can also place the patient in Halo gravity traction after the anterior surgery, in the hope to obtain a gradual correction; however, the literature questions the quantifiable benefit of placing patient preoperatively in halo traction.¹⁷⁷ Current practice, which has been reflected in the literature, has been the use of multiple pedicle screws, multiple Ponte osteotomies and vertebral column resection,¹⁷⁸ instead of performing anterior release.¹⁷⁹ Intraoperative halo femoral traction has

CASE 4

A 14-year-old male, community ambulator with the use of Canadian crutches, was noted to have a progressive scoliotic deformity with minimal pelvic obliquity and no sagittal deformity. Patient is known for an extensive syringomyelia and recurrent tether cord secondary to a L3 myelomeningocele. Patient has had multiple untethering surgeries and failed syngo-plural shut secondary to recurrent posterior spinal wound infection.



The patient meets all the indications for a single anterior spinal fusion and instrumentation. A right-sided anterior approach was chosen based on the right-sided major lumbar curve, which facilitates the discectomies and instrumentation of the lumbar curve. In contrast, the thoracic curve being approached via its concavity makes the discectomies and instrumentation harder as the spine is further away and the disc spaces are collapsed down. Care must be taken while instrumenting the spine from the concavity as the canal orientation differs as to the lumbar curve so the screw trajectory must be adjusted in consequences. Patient was instrumented and fused from T4 to L4.



Single incision, double thoracotomy, with inferior extended into thoracoabdominal approach

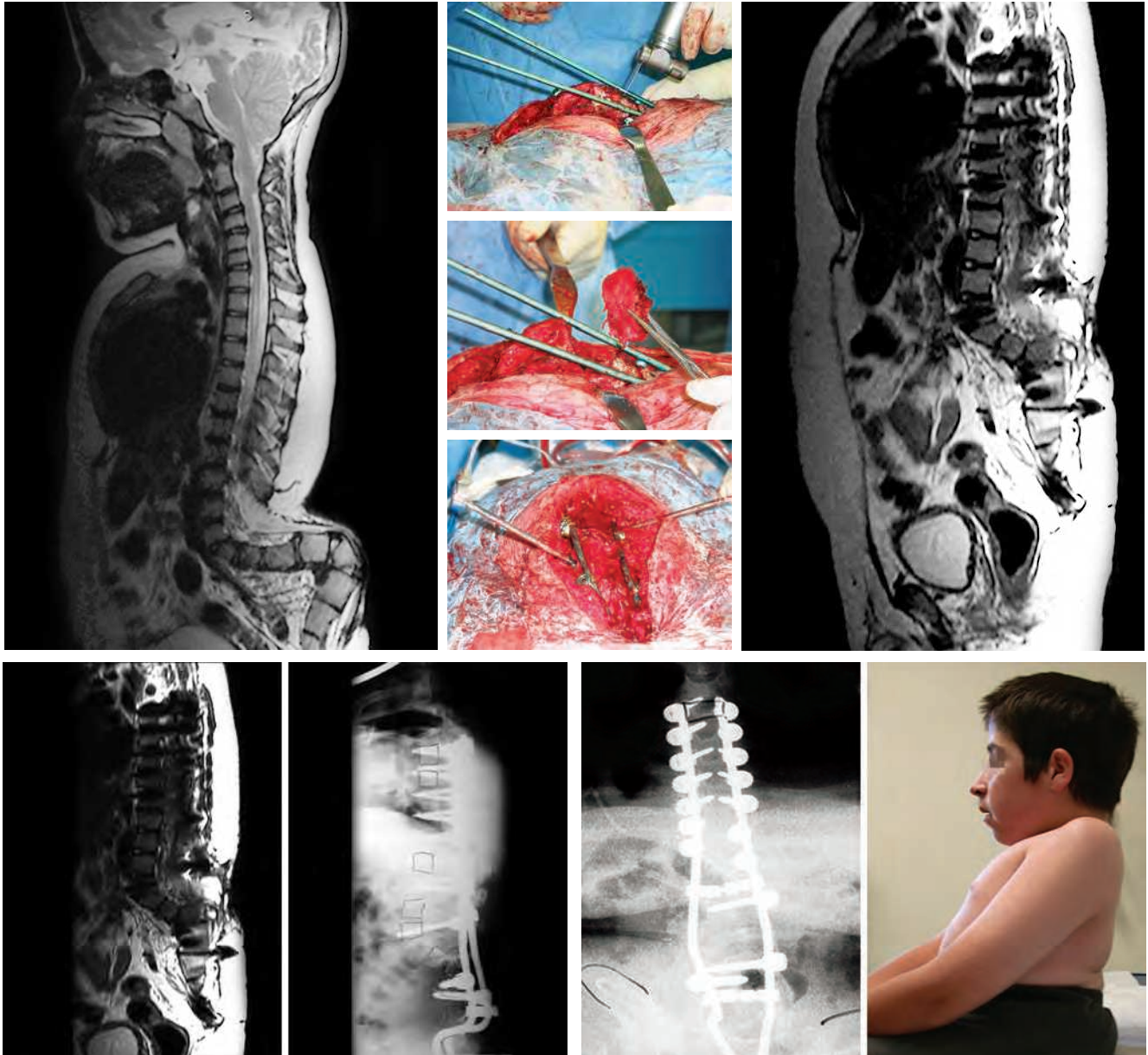


been used to manage severe deformities and severe pelvic obliquity where differential weight is applied to the high pelvic side.¹⁸⁰ Irrespective of the type of trac-

tion, close neurological monitoring either clinically or with intraoperative spinal cord to avoid injury to the spinal cord particularly in patient with residual func-

CASE 5

- A 12-year-old male presented with a severe kyphoscoliotic deformity across the distal thoracic and lumbar spine. Patient underwent a kyphectomy to restore his ability to sit in his wheelchair.
- A closing wedge osteotomy—3 level VCR—proximal to the gibbus was done once the dural sac was mobilized to one side by ligating one set of nerve roots. Dunn McCarthy presacral rods were inserted with modified pedicle screw distally providing adequate distal fixation. Rods were then cantilevered down realigning the spine.



tion¹⁸¹ found a 50% incidence of spinal cord monitoring changes while using halo femoral traction. Complications in staged surgery have been found to be higher and some advocate same day front and back surgery.¹⁸²

Severe Rigid Spinal Deformities

Myelomeningocele patients can present with severe spinal deformities as they often have compounding factors lead-

ing to malignant curve progression. Severe kyphoscoliotic deformities, also known as hairpin deformities are often secondary to a combination of congenital malformation, tethered cords, and erector muscle subluxing anterior to the vertebral bodies. The resulting deformity is considered the end disease of spinal deformities. Such deformities are associated with significant disability and morbidity affecting patient's quality of life: recurrent pressure sores, loss of pulmonary capacity, and loss of sitting independence.¹⁸³

Depending on the overall severity and particularly the rigidity of the coronal and/or sagittal deformities, these deformities may require either multiple Smith Petersen osteotomies, asymmetrical pedicle subtraction osteotomies, versus vertebral column resections. Global kyphotic deformities are best treated with multiple osteotomies¹⁸⁴ while focal kyphotic deformities also called rigid S-shaped kyphosis¹⁸⁵ due to the associated thoracic lordosis above the lumbar kyphosis, are best treated with a kyphectomy. The complication rate for kyphectomies ranges from 20% to 85% consisting of high rate of wound breakdown, deep infections¹⁸⁶ requiring implant removal, implant failure, recurrence of deformities, and death.¹⁸⁷

Early corrective surgery, as described by Nolden et al. consists of acute correction by performing posterior resection of the ossific nuclei at one or multiple levels.¹⁸⁸

When planning a spinal column resection, one must ensure that adequate spinal anchors can be achieved above and below the vertebral column resection (VCR). It is prudent to leave some distal vertebral segments when planning a lumbar VCR, as the risk of distal fixation pull out is high. Solid pelvis fixation should be included in the fixation when performing kyphectomy. The modified Dunn McCarthy¹⁸⁹ presacral rod augmented with pedicle screws in the most distal vertebral bodies provides great distal fixation (Case 6). With such a construction, one is able to cantilever the distal segment and generate considerable force across the resected segment aligning the distal spine and pelvis with the proximal segments, thus correcting the kyphotic deformity. Proximal fixation can be sublamina wire, hooks or pedicle screws. Sharrard was the first describing such apical vertebral.¹⁹⁰

The original technique suggested transection of the dural sac and spinal cord. Others have described to spare the sac by transecting the roots and mobilizing the cord.¹⁹¹ When performing a kyphectomy, the vertebrae contributing to the hairpin deformities are identified and need to be circumferentially dissected. Initiating this extraperiosteal circumferential dissection from both sides at the disc level will minimize the risk of inadvertent laceration/avulsion

of the segmental arteries. The segmental arteries are found at the mid-level of the vertebral bodies,¹⁹² and need to be ligated/cauterized in a controlled fashion. Further, blunt dissection above and below the disc and across the vertebra by detaching the psoas muscle allows complete isolation of the spine. Blunt retractors are placed for either side of the spine, ensuring the great vessel and the peritoneum are protected and reflected anteriorly.¹⁹³ Greater the kyphosis, easier is this dissection as the abdominal content falls forward in the prone position. Once the planed resected vertebrae have been circumferentially dissected, the dural sac has been transected or mobilized and blunt retractors are protecting the great vessels. The vertebra can be cut with an oscillating or Gigli saw at a bony surface, thus providing good bony apposition. As one does this, one encounters significant blood loss, and it persists until the two ends of the vertebrectomy have been approximated. Having the rods already anchored distally prior to resection saves time and allows for controlled reduction. That is why, the spinal anchorage points must be already in place and that the actual kyphectomy is done last (Case 5).

Young Myelomeningocele Patient

Young patient with progressive spinal deformities and with significant growth poses an even greater challenge. The timing of managing this severe sagittal spinal deformity has been advocated at all ages. In the newborn and young infant, one can achieve significant correction by performing posterior resection of the ossific nuclei at one or multiple levels.¹⁹⁴

However, initiating a surgical management in these young patients with progressive spinal deformities and with significant growth poses an even greater challenge.

Growth, sparing procedures, such as growing rods and VEPTR carry by themselves a high complication rate centered on wound issues and spinal anchor failures, both of which myelomeningocele patients are prone to develop. Smith et al¹⁹⁵ have advocated the management of early myelomeningocele kyphotic spinal deformity using rib to pelvic growth-sparing fixation (Case 6). Conceptually, this technique is advantageous as it maintains spinal length and growth. Additional advantage of using rib-to-pelvis instrumentation in the incisions are well away from the midline spinal dysraphism area minimizing the risk of infection or skin breakdown. Initial results have been promising in the nonambulating patients. In the ambulating patients, they have noted that over time, the repeated lengthening

CASE 6**A. Preoperative**

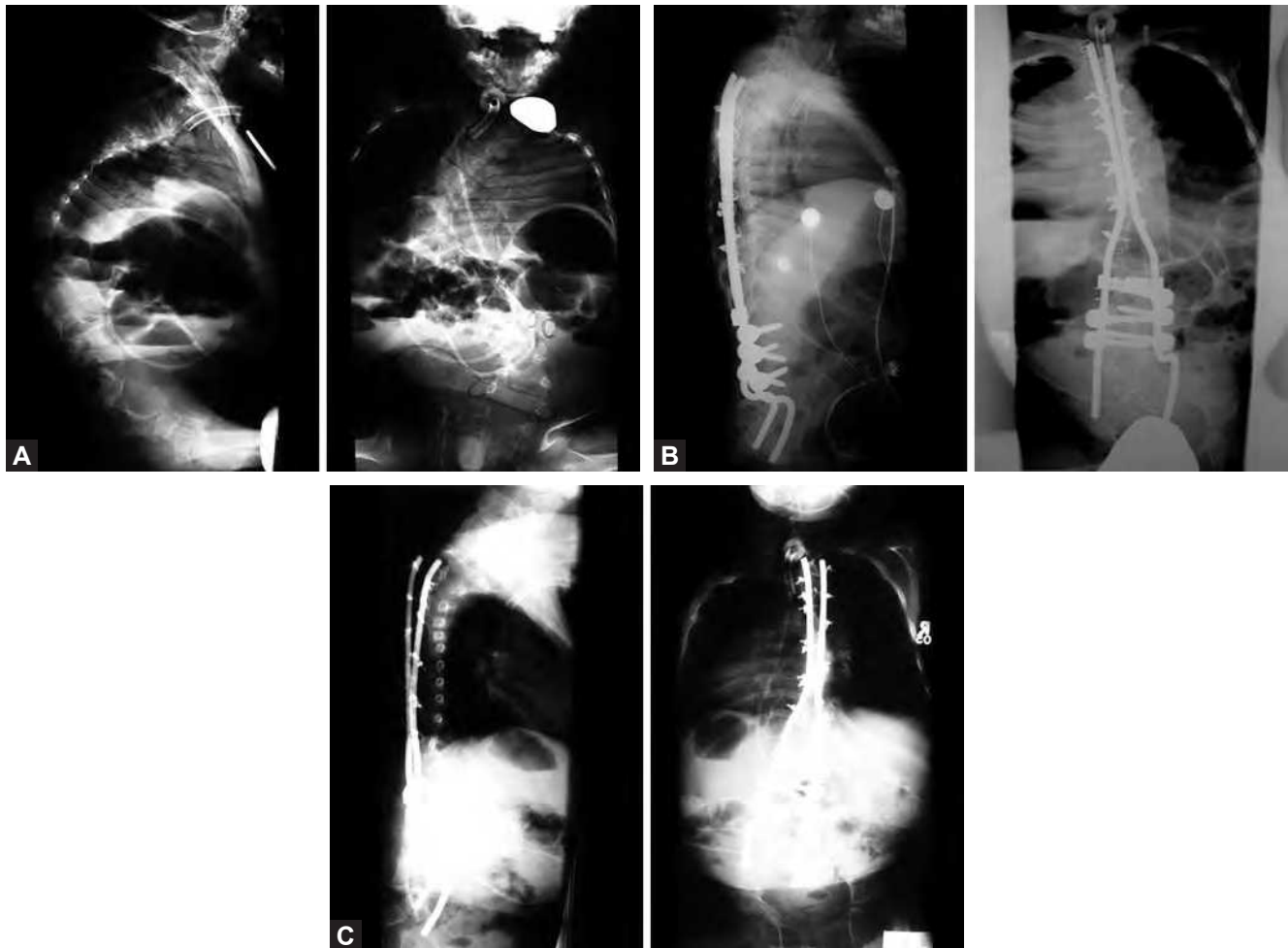
- A 6-year-old patient with L1 myelomeningocele, central apnea secondary to severe Arnold-Chiari requiring a tracheostomy. Presented with progressive kyphoscoliosis and pelvic obliquity.

B. Postoperative

- Patient underwent posterior spinal instrumentation with distal S rod pelvic fixation and modified pedicle screw to counteract kyphotic forces and altered myelomeningocele anatomy, while proximal fixation consisted of Luque trolley-type gliding fixation for growth.
- Lumbar interbody fusion was undertaken via PLIF type approach with multiple discectomies and cancellous bone grafting.
- Correction maneuver consisted of obtaining distal fixation with S rods and lumbar screws and cantilevering rods down and across correcting both coronal and sagittal deformities

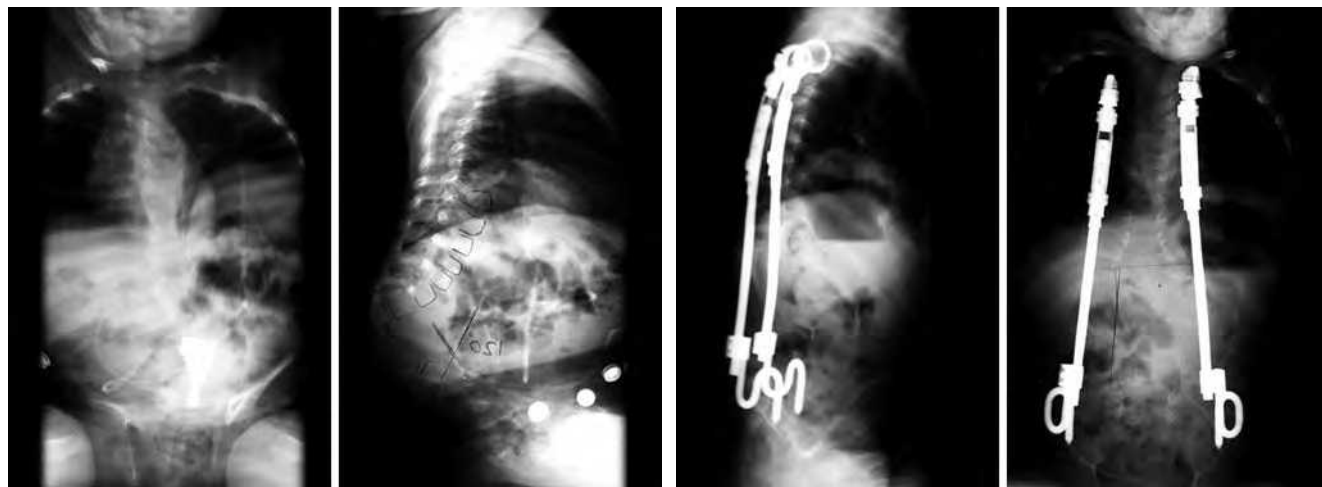
C. Postoperative (3 years)

- Three years postoperative patient's correction remain acceptable with evidence of spinal growth with sublaminar wire traveling proximally. However, patient is developing proximal junctional kyphosis. In addition, pelvic S rods are shifting along pelvic rim. Both of these complications may require revision surgery as some point to prevent progressive deformity.



CASE 7

A 5-year-old girl with severe lumbar kyphosis underwent growth sparing spinal surgery with insertion of bilateral rib-to-pelvis fixation—VEPTR. Gibbous was obviously flexible allowing for significant correction, and maintenance of spinal height.



is kyphogenic in nature and alters the pelvic parameters rendering their gait awkward. This technique is promising. However long-term results are still lacking. Other techniques¹⁹⁶ can be considered for the very young myelomeningocele patients such as hybrid constructs where the primary lumbar curve and the pelvic obliquity are corrected and fused while the thoracic curve is not fused but only instrumented using a Luque trolley type fixation allowing ongoing growth and development of the chest wall and thoracic spine¹⁹⁷ (Case 7).

In summary, managing spinal deformities in the patient with myelomeningocele requires a good knowledge of spinal anatomy, meticulous attention to skin-handling and vigilant aseptic techniques. Preoperative planning is essential, and focusing on skin incision, type of fixation, and anterior column fusion minimizes perioperative complications. Despite good perioperative management, complications remain high and are best managed in a multi-disciplinary fashion.

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Chiari Malformation and Syringomyelia

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Snapshot

- » Diagnosis
- » Clinical Presentation
- » Syringomyelia
- » Pathogenesis
- » Treatment
- » Complications
- » Results and Prognosis

INTRODUCTION

Chiari malformations are a collection of posterior cranial fossa abnormalities due to abnormalities in rhombencephalon descent and cerebellar ectopia. Although Hans Chiari was not the first person to describe these hindbrain abnormalities, his report in 1891 originally classified two types of these rhombencephalic anomalies. Subsequent work over the last century has further distinguished more subtypes. The two most common and major subtypes are type I and type II malformations, which are believed to be pathologically distinct disorders.

Chiari type I malformation (CIM) is most common and is defined as the herniation of the cerebellar tonsils >5 mm below the foramen magnum, with no associated brainstem herniation or myelodysplasia. Cervical syringomyelia is the most common associated finding with this subtype. In contrast, Chiari type II malformation is always associated with myelodysplasia and involves herniation of the brainstem and vermis, in addition to the cerebellar tonsils, through the foramen magnum. Syringomyelia is also commonly seen with Chiari type II malformation.

Chiari type III, the rarest and most severe form of these disorders, involves an occipital or high cervical encephalocele that contains herniated cerebellar or brainstem tissue. Chiari type IV, which involves hypoplasia or aplasia

of the cerebellum, has a relatively normal posterior fossa size and no cerebellar herniation. Recently, there have been descriptions of new variants such as “Chiari 0” malformation, which is syringomyelia without cerebellar tonsil herniation, and “Chiari 1.5” malformation, which is Chiari I and additional brainstem herniation without myelodysplasia.¹⁻³ This chapter will focus primarily on the pathophysiology of CIM given its prevalence and onset in adolescence and adulthood.

DIAGNOSIS

Radiographically, CIM is defined as herniation of the cerebellar tonsils of 5 mm or greater below the foramen magnum, in the absence of any intracranial lesion or malformation that may lead to increased intracranial pressure. Recent advances in imaging have revolutionized the diagnosis of Chiari malformation. In a study of 200 normal patients and 25 patients diagnosed with CIM, Barkovich et al. concluded that tonsillar herniation of <2 mm is likely of little clinical significance in the absence of syringomyelia.⁴ They also demonstrated that 14% of normal patients had tonsils extending slightly below the foramen magnum and 1 in 200 normal patients had tonsils 5 mm or below the foramen magnum by magnetic resonance imaging (MRI).

Aboulezz et al., in a study reviewing >800 MRI examinations, found that up to 3 mm of tonsillar herniation is



Fig. 23.1: Sagittal T2 magnetic resonance imaging demonstrating Chiari I malformation.

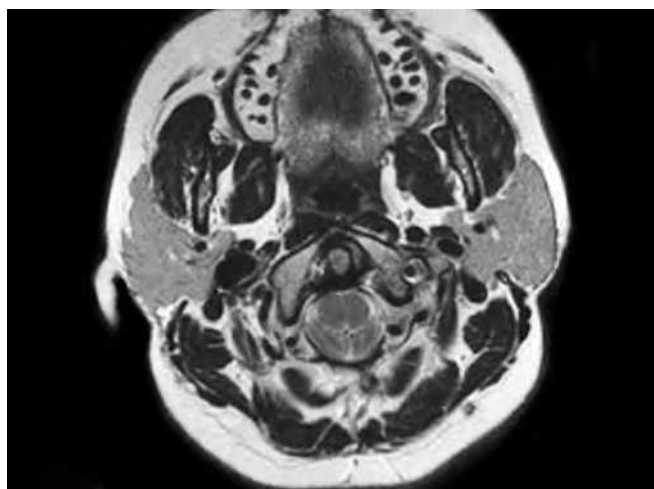


Fig. 23.2: Axial T2 magnetic resonance imaging demonstrating crowding of the cerebellar tonsils at the level of the foramen magnum.

normal but may be pathologic when exceeding 5 mm, with borderline cases between 3–5 mm.⁵ However, the authors note mild ectopia between 3–5 mm should be considered significant, if there are neurological symptoms, syringomyelia, cervicomedullary kinking, or peglike appearance of the cerebellar tonsils.⁶ No significant correlation has been found between the severity of symptoms and the extent of herniation.¹ Importantly, it is notable to consider that cerebellar tonsils ascend with age, such that 6 mm herniation is considered pathologic in the first decade of life (Figs. 23.1 and 23.2).⁶

Mechanisms Causing Chiari Malformation

Several mechanisms leading to cerebellar tonsil herniation in CIM have been proposed, including cranial constriction, spinal cord tethering, cranial settling, intracranial hypertension and intraspinal hypotension.⁷ Cranial constriction is seen in patients with craniosynostosis, achondroplasia, acromegaly, and Paget's disease and is associated with a smaller area of the foramen magnum outlet. Spinal cord tethering is seen in those with Chiari type II malformation and leads to an abnormally enlarged foramen magnum. Spinal cord tethering may be more rarely seen with a fatty filum terminale in cases without spinal dysraphism.

The remaining three mechanisms of cerebellar herniation do not have an abnormal posterior cranial fossa dimension and likely represent distinct etiologies. Cranial settling is seen in patients with hereditary disorders of connective tissue or post-traumatic patients with

occipitoatlantoaxial joint instability. Intracranial hypertension is found in patients with hydrocephalus, posterior fossa masses, subdural hematomas, or other intracranial mass lesions. Intraspinal hypotension is seen in patients with a prolonged lumboperitoneal shunt, cerebrospinal fluid (CSF) leaks, or dural ectasias.^{1,7}

CLINICAL PRESENTATION

The clinical presentation of patients with CIM varies widely, from subtle headache to myelopathy and symptoms of brainstem compression.² Occipital headache and upper cervical pain induced by laughing, sneezing, or coughing is the most common presentation.⁸ In addition, more than half of patients also have some ophthalmologic symptoms (blurry vision, nystagmus, and visual field deficits) and otologic disturbances (tinnitus, hearing loss and vertigo).⁹

Other symptoms resulting from myelopathy and brainstem compression include motor and sensory deficits, hyper-reflexia, ataxia, lower cranial nerve deficits, and loss of pain and temperature sensation. Myelopathy can result from direct cord compression or syringomyelia, with the syrinx most commonly found in the cervical area. Without treatment, a syrinx can lead to progressive myelopathy with sensory and motor functional loss, and can produce progressive spinal deformity.¹⁰

Young children <3 years old often present with lower cranial nerve dysfunction that leads to poor feeding, dysphagia, diminished gag reflex and vocal cord paralysis.¹¹ Sleep apnea due to airway collapse may lead to sudden

death. Reviewing MRI studies, Trigylidas et al. found a significant reduction in the volume of the posterior cranial fossa in symptomatic Chiari type I patients compared to asymptomatic patients aged 10–18 years. No difference was found in patients <10 years of age however.¹² These results underline the importance of monitoring asymptomatic patients for the development of symptoms later in life.

■ SYRINGOMYELIA

In symptomatic Chiari type I patients, syringomyelia can be found in 40–85% of the times, with this prevalence being smaller in asymptomatic patients.^{1,13} Communicating syrinxes were found in association with hydrocephalus and in conditions, such as Chiari type II and Dandy-Walker malformation. Noncommunicating syrinxes were seen predominantly in adults and in disorders that affect CSF dynamics such as CIM, basilar impression, and arachnoiditis. These isolated syrinxes are cavities that dissect paracentrally into the spinal cord and are lined with glial scar and myelomalacia.

■ PATHOGENESIS

Chiari type I malformations are congenital forms of cerebellar herniation at least 5 mm below the level of the foramen magnum. Many hypotheses have been proposed about their pathogenesis. Some leading theories include hindbrain dysgenesis, developmental arrest theory, caudal retraction theory, the Gardner's hydrodynamic theory, small posterior fossa theory, and lack of embryologic ventricular distension theory.

Chiari type I and type II malformations most likely share different pathophysiologic origins. However, the impaired CSF flow across the craniocervical junction, seen in both CIM and Chiari type II malformation, probably leads to the development of syringomyelia.

Chiari I Malformations

There are both congenital and acquired causes for CIM. In regard to congenital CIMs, mesodermal defects can lead to a small posterior fossa. A small posterior fossa can cause compression of the neural elements and herniation through the foramen magnum, which can lead to subsequent alteration of CSF flow. Aberrant CSF flow may lead to the symptoms seen in CIM. Furthermore, CIM is often seen with other mesodermal defects, such as other spine, skull, somatic, and craniofacial abnormalities. Abnormalities of the upper cervical spine include hypermobility of

the craniovertebral junction, Klippel-Feil syndrome, occipitalization of the atlas, and anterior indentation of the foramen magnum (either basilar invagination or retroversion of the odontoid process). Chiari I malformation is also strongly associated with craniosynostosis, especially the syndromic, multisuture, and lambdoid synostosis types. Certain types of synostosis can either decrease the volume of the posterior fossa or cause elevated intracranial pressure, facilitating the herniation of posterior fossa contents.²

Besides mesodermal defects, there can be acquired causes of CIM. The presence of a craniospinal pressure gradient across the foramen magnum can promote formation of CIM. For example, if the spinal compartment has a relative negative pressure compared to the intracranial compartment, this can cause a “sump effect” upon the cerebellar tonsils into the foramen magnum. Iatrogenic means, such as repetitive lumbar punctures, lumbar drainage, chronic CSF leaks, and lumboperitoneal shunting, can cause acquired CIM.²

Syringomyelia

A number of theories have been proposed to explain the development of syringomyelia in CIM. Gardner's “hydrostatic theory” suggests that retained communication of the central canal with the fourth ventricle, secondary to delayed embryonic opening of the fourth ventricle's outlets, leads to hydrodynamic stresses in embryonal and early fetal life with resultant syringomyelia.¹⁴

Williams' “craniospinal pressure dissociation” hypothesis is also predicated on a persistent connection between the fourth ventricle and the central canal. This theory notes that there is difficulty in rapidly equilibrating CSF pressure wave seen during valsalva. During this delay, there is a vector of force out of the intracranial cavity, and the prolonged pressure differential results in downward migration of the cerebellar tonsils, resulting in the obstruction of CSF flow between the posterior fossa and the cervical subarachnoid space. This leads to continued fluid flow into the central canal from the fourth ventricle.¹⁵

In contrast, with the knowledge that there is rarely a communication between the ventricular system and a syrinx, using phase contrast MRI, Oldfield found that the cerebellar tonsils in Chiari type I patients partially occlude the subarachnoid space at the foramen magnum. The increased pressure in the subarachnoid space leads to diffusion of fluid through the perivascular space of the spinal cord and formation of a syrinx. Authors have noted this theory fails to account for the higher pressure found

in the syrinx than the subarachnoid space, the different composition of syrinx fluid than that of CSF, and the presence of extensive gliosis and wall thickening found in the syrinx.¹⁶⁻¹⁸

More recently, studies in animal models and fluid dynamics imaging have suggested the role of arterial pulsation in syrinx formation, as Chiari type I patients were found to have a prolonged systolic flow pattern, leading to CSF penetration into the spinal cord.^{19,20} Combining these different ideas, Levine proposed a unified hypothesis where obstruction of CSF flow at the foramen magnum leads to changes in the transmural pressure of the vessels above and below the blockage. While capillaries and veins above the blockage dilate, those below the blockage collapse, resulting in mechanical compression of the spinal cord. This chronic stress on the spinal cord leads to parenchymal injury, breakdown of the blood-spinal cord barrier, and accumulation of fluid in the region of the damaged spinal cord, ultimately leading to syrinx formation.

TREATMENT

Appropriate patient selection for surgical decompression can be challenging, and surgical indications vary from surgeon to surgeon. As patients respond best when operated on within 2 years of onset of symptoms, early surgery is recommended for symptomatic patients. Asymptomatic patients should be followed in clinic and operated upon, if the patient becomes symptomatic, although many surgeons consider radiographic development of a syrinx to be adequate indication for operative intervention.

In a patient suspected of having CIM, the patient should undergo an MRI of the posterior fossa as well as the entire cervical spine to screen for a syrinx. Long-tract signs on physical examination without evidence of cervical syrinx should also warrant MRI of the thoracic and lumbar spine. Brain imaging should be obtained to rule out hydrocephalus.

The presence of a syrinx suggests that there are pathologic forces upon the spinal cord. A small, asymptomatic syrinx may be followed with serial follow-up and imaging. In patients without a syrinx and who are minimally symptomatic (mild headache), observation and clinical follow-up may be appropriate. Surgery can be deferred until symptoms progress or headaches become refractory to conservative treatment. Patients with severe headaches or objective neurologic findings should receive earlier surgical intervention.

In patients with concomitant hydrocephalus or elevated intracranial pressures, the hydrocephalus should be treated first. Ventriculoperitoneal shunting or third ventriculostomy are options to treat the hydrocephalus. If symptoms persist or if an associated syrinx remains unchanged after observation, even after shunting or third ventriculostomy, then a posterior fossa decompression should be considered.

Chiari Decompression

The aim of the surgery is to restore the natural CSF dynamic flow from the fourth ventricle to the subarachnoid space and decompress the brainstem. There are currently no known nonsurgical means of treatment for symptomatic CIM.

The patient is placed in a prone position on chest rolls with the head flexed and secured in a Mayfield headholder. The neck is flexed to open the interspace between the occiput and posterior arch of C1. The shoulders can be retracted inferiorly with tape (Fig. 23.3).

A midline incision is made from theinion to the level of the C2 spinous process. Staying midline separates the soft tissue and muscles along an avascular plane (Fig. 23.4).

The foramen magnum and the C1 posterior arch are exposed the width of the cervical dura. The bone above the foramen magnum is removed, generally approximately 5 cm high by approximately 5 cm wide, although smaller craniectomies are favored by some surgeons. Overly aggressive resection of the occipital bone can lead to



Fig. 23.3: Patient positioning. The patient is positioned prone for a midline posterior fossa approach. The patient's head is translated posteriorly and flexed. Flexing the head opens the foramen magnum-C1 interval. The patient is placed on chest rolls to prevent an increase in intrathoracic pressure. *Source:* Taken from *Core Techniques in Operative Neurosurgery* by Jandial.

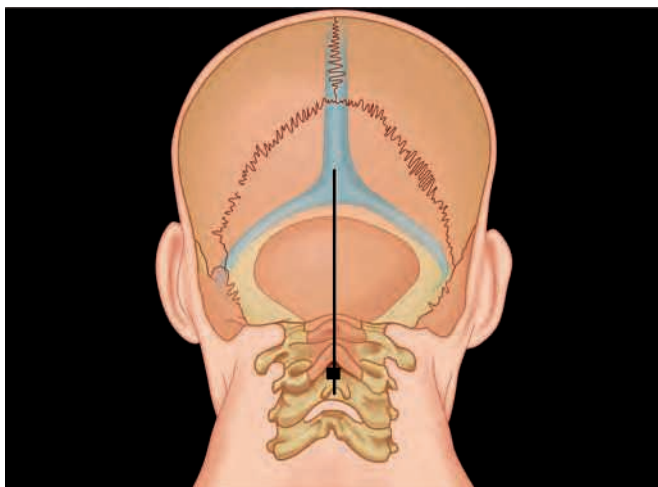


Fig. 23.4: Incision for a Chiari malformation decompression. A midline incision is made from the inion down to the level of the cervical lamina one level below the lowest extent of the cerebellar tonsils.

Source: Taken from Atlas of Neurosurgery by Meyer.

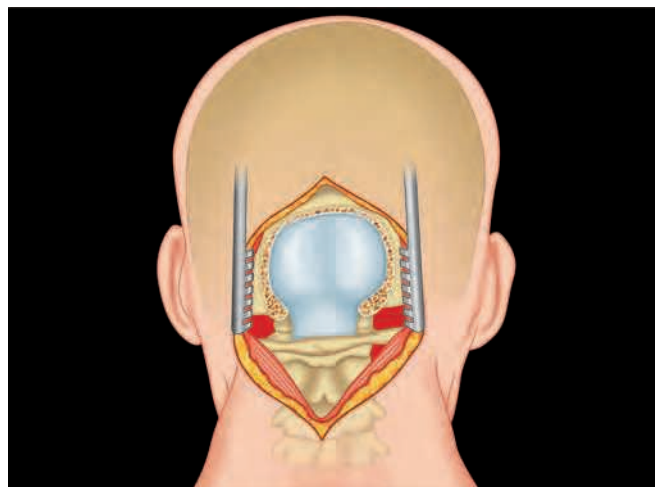


Fig. 23.5: Craniectomy for a Chiari malformation decompression. The craniectomy should be approximately 5 cm high by approximately 5 cm wide above the foramen magnum. The rim of the foramen magnum is cut with a rongeur to extend the opening laterally to the occipital condyles. A laminectomy of C1 is also performed.

Source: Taken from Core Techniques in Operative Neurosurgery by Jandial.

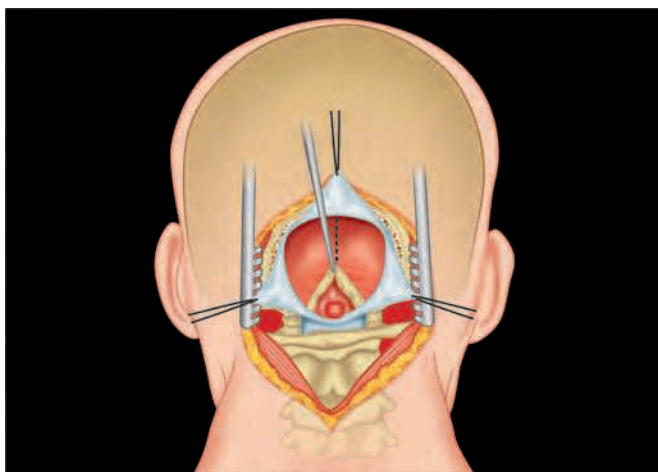


Fig. 23.6: Dural opening. The dura can be opened in a Y-shaped fashion. The superior limb of the dura extends to the inferior aspect of the transverse sinus.

Source: Taken from Core Techniques in Operative Neurosurgery by Jandial.

cerebellar sag and herniation. A C1 laminectomy is performed. Usually, a C2 laminectomy is unnecessary; maintaining the muscle attachments and lamina of C2 minimizes postoperative pain (Fig. 23.5).

The dura is then opened in a Y-shaped fashion. The tonsils can gently separated to inspect for veils or adhesions covering the outlets of the fourth ventricle. Some surgeons choose to use bipolar cautery to shrink the ton-

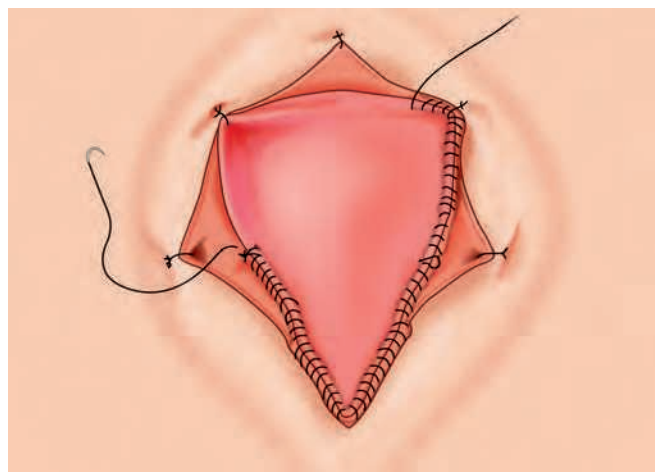


Fig. 23.7: Dural graft is sewn in place in a watertight fashion.

Source: Taken from Atlas of Neurosurgery by Meyer.

sillar tips or to perform lysis of subarachnoid adhesions to restore CSF flow. Many surgeons perform only opening of the dura, and try to remain extra-arachnoid in placing a dural graft, with the rationale that restoration of CSF hydrodynamics may be accomplished simply by allowing for greater expansion of basal arachnoid cisterns (Fig. 23.6).

A dural graft is then sewn to provide a more spacious posterior fossa. Pericranium or fascia lata may be harvested for the graft, or artificial dural graft may be used (Figs. 23.7 and 23.8).

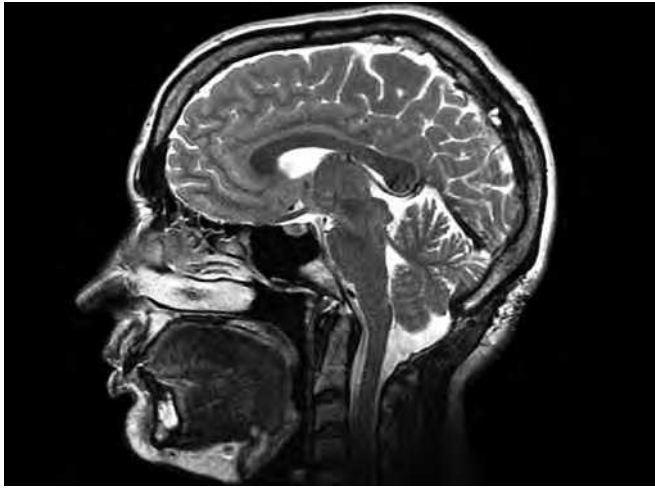


Fig. 23.8: Sagittal magnetic resonance imaging demonstrating decompression of posterior fossa and foramen magnum.

COMPLICATIONS

Chiari decompression is a significant cranial procedure and is not without risk. Risks include CSF leak, pseudo-meningocele, herniation of cerebellar hemispheres, vascular injury (especially the posterior inferior cerebellar arteries), and meningitis. Although occipital-cervical instability is a potential complication, cervical kyphosis or postoperative instability is rarely seen. Cerebrospinal fluid leaks developing in the postoperative period may be indicative of previously unappreciated hydrocephalus, which may require treatment via ventriculoperitoneal shunting procedures.

In one study of 71 patients, one patient died from sleep apnea, and respiratory depression, the most commonly seen complication, was seen in 10 patients.²¹ In another series of 130 patients, acute postoperative hydrocephalus due to infratentorial hygroma was seen in 2 patients, and temporary external ventricular drainage was required.²² In this same series, a retroflexed odontoid process was seen in only one patient who required a transoral odontoidectomy. Posterior fossa craniectomies that extend too laterally have the risk of “cerebellar slump”, where the cerebellum herniates through the craniectomy defect. This may cause headaches that are different in quality than typical Chiari headaches, but may be remedied with a cranioplasty to support the cerebellum into correct position.

RESULTS AND PROGNOSIS

The main goal of surgery is to halt the progression of symptoms. Patients with preoperative complaints of pain may

respond well to surgery, although predicting outcomes with regard to relief of headache symptoms can prove difficult. Furthermore, syrinxes should decrease over months after surgery. Motor weakness is less responsive to surgery, especially if muscular atrophy is already present.²³ Factors that correlate to a worse outcome are the presence of atrophy, ataxia, scoliosis, and symptoms lasting longer than 2 years.²³

Poor clinical resolution of CIM may be due to inadequate decompression. In patients who initially improve with decompression and then worsen at a latter time, return of CSF flow compromise may have developed. These patients will usually respond to repeat decompression; some may also consider resection of portions of the cerebellar tonsils. In patients with persistent syrinxes, unresponsive to adequate surgical decompression, a syringopleural or syringoperitoneal shunt may be considered.

KEY POINTS

- Chiari malformation involves disruption of normal CSF flow through the foramen magnum. Occipital and upper cervical pain, induced by laughing, sneezing, or coughing, is the most common presentation. Other symptoms resulting from myelopathy and brainstem compression include motor and sensory deficits, hyper-reflexia, ataxia, lower cranial nerve deficits, and loss of pain and temperature sensation. Syringomyelia is also commonly seen in CIM.
- Treatment of CIM, when indicated, is surgical. The purpose of surgery is to enlarge the posterior fossa, restore normal CSF outflow from the fourth ventricle, and relieve brainstem compression.
- After decompressive surgery, there is generally resolution of Chiari malformation symptoms as well as resolution of syrinxes, if they are present.
- Complications of surgery are usually minimal; however, there is always a risk of CSF leak, pseudomeningocele, damage to neural or vascular structures, meningitis, and respiratory depression.
- Treatment of a syrinx, when not the result of cerebellar tonsil herniation, includes shunting of the syrinx into the adjacent subarachnoid space, peritoneum, or pleura.

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- This paper reviews the theories for syrinx formation. This paper also proposes a new theory that takes into the shortcomings of the other theories.

The Spine in Osteogenesis Imperfecta

Andrew H Milby, Paul W Esposito, Vincent M Arlet

Snapshot

- » Diagnosis and Medical Therapy
- » Perioperative Considerations
- » Natural History of Spinal Manifestations
- » Surgical Indications and Clinical Outcomes
- » Technical Considerations

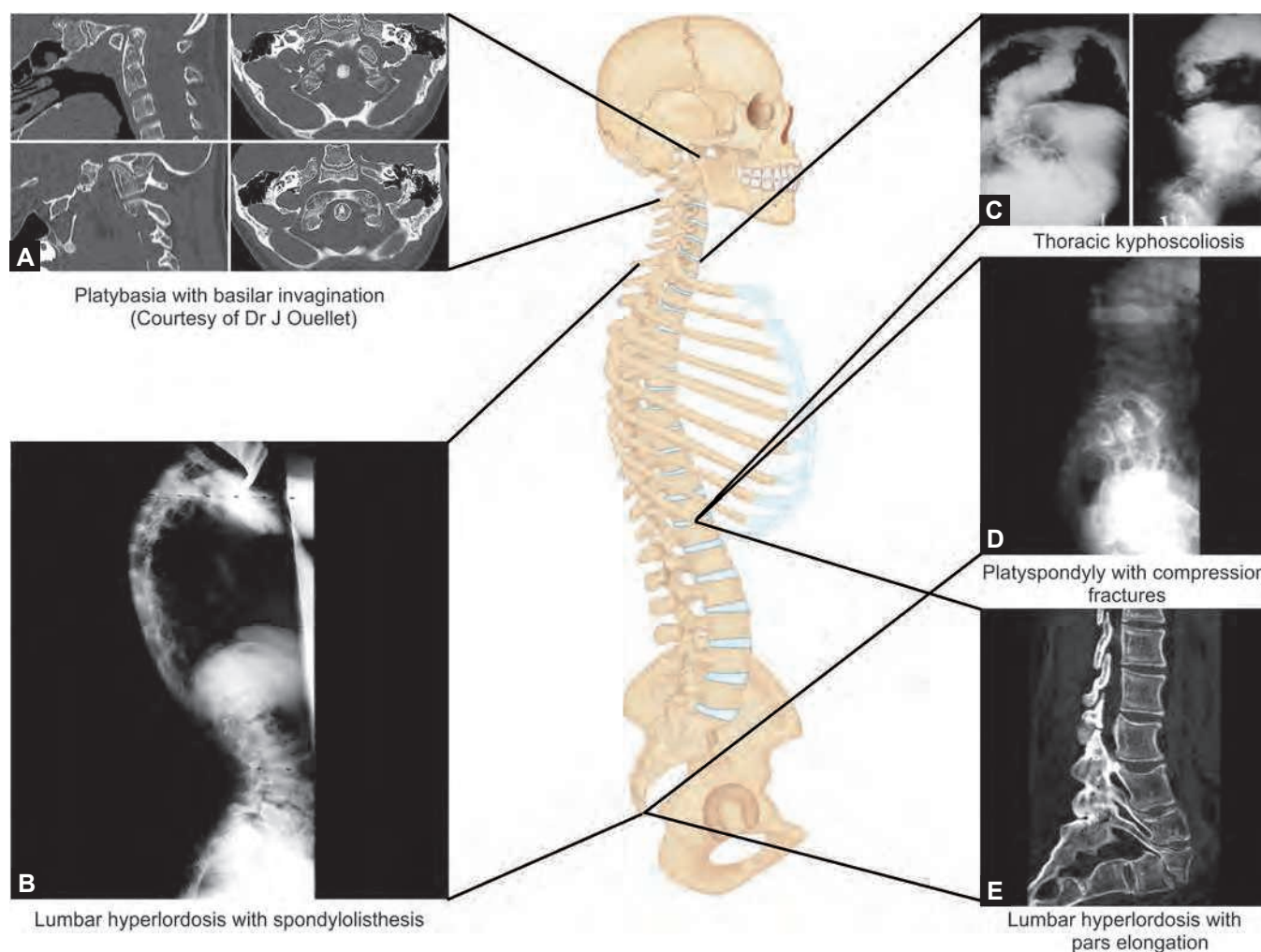
INTRODUCTION

Osteogenesis imperfecta (OI) is a rare but serious heritable disorder of collagen synthesis with variable and wide-ranging skeletal manifestations. These classically include osteoporosis with increased bone fragility, ligamentous laxity, short stature or dwarfism, and deformities of the spine, pelvis, and long bones. Additional characteristic nonorthopedic manifestations, such as blue sclerae, hearing loss, and defects of dentinogenesis, may be present. Numerous historic accounts of familial “brittle bone disease” exist, with the first scientific description by in the doctoral thesis of Olof Jakob Ekman in 1788.¹ The disease terminology was inconsistent until the first use of the term “osteogenesis imperfecta” by Willem Vrolik.¹ Recent advances have allowed for more detailed subclassification based upon the molecular pathophysiology of the disease variants; however, overall prevalence is estimated at approximately 16 cases per million and is evenly distributed across ethnic groups.²

The genetics and specific phenotypic subtypes of OI were first subclassified by Sillence et al.³ Incidence ranges from 1 to 2 per 100,000 births for severely deforming autosomal recessive type III to 3 to 5 per 100,000 births each for both mild autosomal dominant type I and severe autosomal recessive type II. While historically lethal in the perinatal period, survival into the perinatal period with type II disease is now possible with modern treatment.

The incidence of the autosomal dominant type IV form is unknown. Numerous abnormalities of the *COL1A1* and *COL1A2* genes have subsequently been identified, which result in quantitative or qualitative abnormalities in synthesis of type I procollagen.^{4–6} Types I and IV are subclassified into A and B variants based on the absence or presence of associated dentinogenesis imperfecta. The four initial types described by Sillence et al. have been expanded upon by Rauch and Glorieux et al., who described types V, VI, and VII, which produce OI-like disease states without evidence of type I collagen abnormality. Instead, other etiologies have been proposed, such as defects in remodeling capacity and osteoid mineralization.^{7–9} In addition, Cabral et al. have described an autosomal recessive type VIII caused by a defect in cartilage-associated protein, which participates in the process of collagen hydroxylation.¹⁰

Multiple manifestations of OI have been described affecting the cervical, thoracic, and lumbar spine (Figs. 24.1A to E). Across all subtypes, approximately 60% of subjects with OI exhibit some form of spinal deformity, ranging from nearly 90% in severe congenital forms to 10–40% in the less severe forms previously described as mild tarda forms.¹¹ Abnormalities of the craniocervical junction (Figs. 24.2A to D), thoracic kyphoscoliosis, lumbar hyperlordosis, and spondylolisthesis have been observed. Kyphoscoliosis is the most common finding, typically associated with multiple vertebral compression fractures and/or rib fractures, and may result significant thoracic deformity. The vertebral



Figs. 24.1A to E: Spinal manifestations of osteogenesis imperfecta.

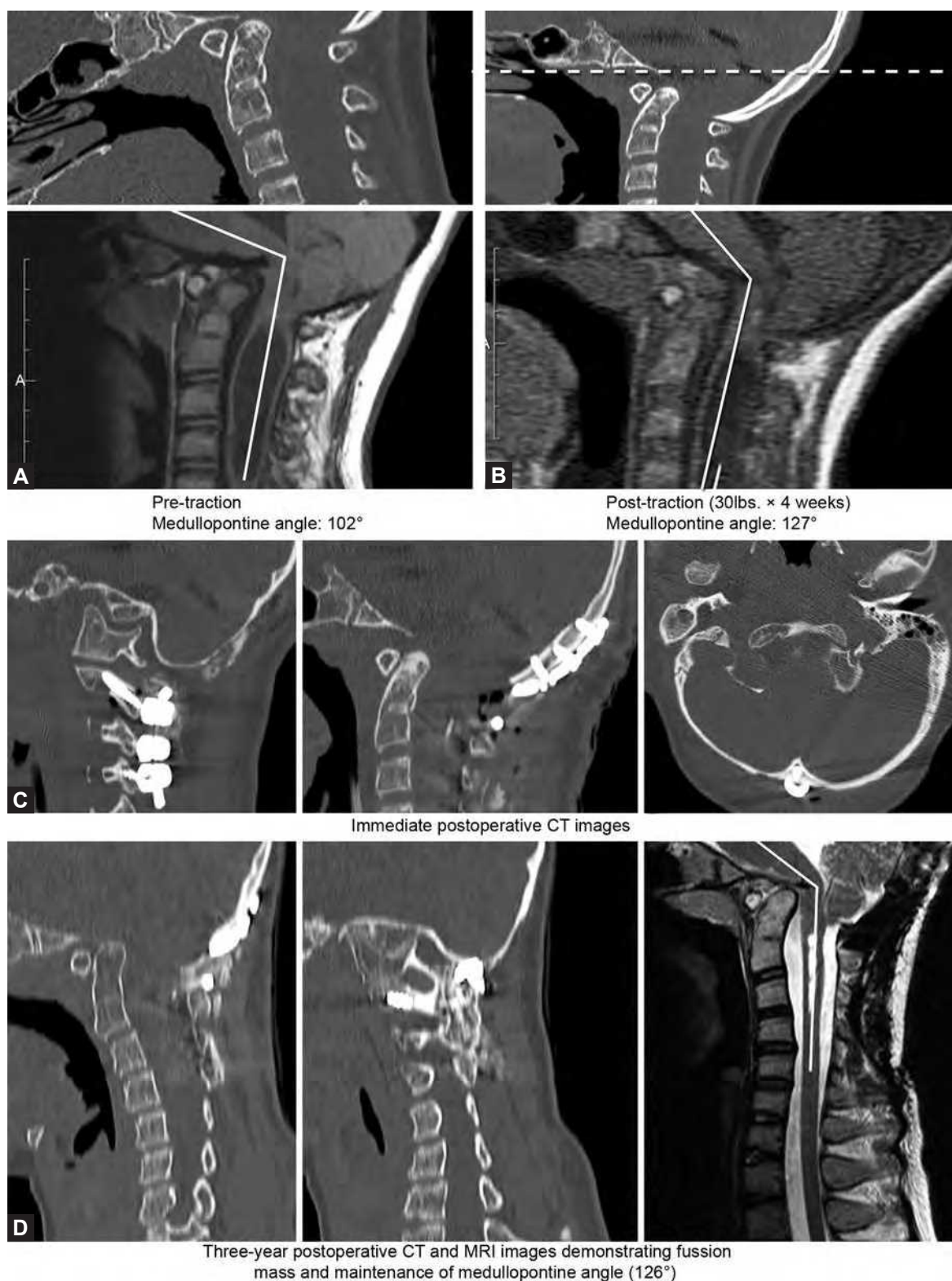
bodies are often flat or biconcave due to accumulated osteoporotic microfractures. The resulting spinal deformity may result in significant morbidity due to impaired respiratory function, delayed motor milestones, and poor quality of life.^{12,13}

DIAGNOSIS AND MEDICAL THERAPY

While tissue typing and molecular and genetic testing have become increasingly widespread, the diagnosis of OI remains primarily clinical. The combination of multiple fractures in the setting of minimal trauma, along with characteristic osseous and nonosseous deformities as previously described with supporting radiographic evidence, may be highly suggestive of the diagnosis. Advances in fetal ultrasound have made it possible to prenatally iden-

tify structural features of OI but is not completely accurate in predicting the diagnosis or severity of the disorder.¹⁴ Postnatally, molecular studies may be performed from culture of skin fibroblasts, which confirm a defect in type I collagen synthesis in approximately 90% of patients.¹⁵ In children with less severe or obvious clinical phenotypes, dual-energy X-ray absorptiometry scanning may reveal significant reductions in bone mineral density compared to age-matched controls.¹⁶ Other conditions in the differential diagnosis of OI include fibrous dysplasia, hematologic malignancies, hypophosphatasia, and idiopathic juvenile osteoporosis. In addition, nonaccidental trauma must be excluded in any case where multiple fractures are present in various states of healing.

While numerous surgical interventions have been described for acute fracture management, early systemic



Figs. 24.2A to D: Basilar invagination treated by reduction with halo gravity traction followed by posterior occipitocervical decompression and fusion.

Courtesy: Jean Ouellet, MD (Montreal, Canada).

medical therapy for OI is essential to maximize bone mineral density and reduce fracture risk. A multidisciplinary team effort is required to optimize diet, vitamin D and calcium intake, as well as appropriate guided activities to ensure safe but maximal psychomotor development. Bisphosphonate medications have been shown to increase cortical thickness and trabecular bone volume via reduction of osteoclast activity, and are a mainstay of pharmacologic treatment.^{17,18} When used in infancy for treatment of severe cases, bisphosphonates have shown short-term safety and efficacy in maintaining mobility and prevention of secondary deformities.^{19,20} Bisphosphonates have also resulted in improved vertebral height and development in children with compressed vertebral bodies.²¹ Despite its benefits for prophylaxis, the potential for impaired fracture or osteotomy healing and decreased rate of remodeling with ongoing use of bisphosphonates must be considered in the setting of acute fracture or surgical intervention.¹⁸

■ PERIOPERATIVE CONSIDERATIONS

Despite optimal medical management, patients with OI often require surgical intervention for acute injuries or progressive deformity. It is imperative that the surgeon and anesthesiologist consider the systemic physiologic effects of the disease process in the perioperative setting. Handling of the anesthetized patient with OI requires additional vigilance on the part of the operating room staff to prevent inadvertent injury.²² The treating surgeon should ensure that entire surgical team is aware of the risks of extremity fractures during positioning, and should be present during positioning and transferring to and from the operating room table. Stabilization of the cervical spine by the surgeon during intubation and positioning of the patient is important to prevent cervical injuries. Positioning of the patient on the operating room table may also be challenging due to thoracic or pelvic malformations, and/or stiffness or malunion of the extremities. Standard tables may not be appropriate, and proper planning as well as creativity is necessary to optimize safe positioning while respecting the general rules that apply to all spinal procedures (Figs. 24.3A to F). Postoperatively, with the collaboration of the parents, the nursing team must also be aware of the increased potential for injury. Abnormal facial and cranial morphology may result in difficulties with airway management, as does the increased risk of dental injury.²³ Thoracic deformity may result in compromised respiratory function. While under general anesthesia, a tendency toward hyperthermia with diaphoresis has been reported

in patients with OI,^{24,25} though a recent series reported similar intraoperative temperature and end-tidal carbon dioxide measurements between groups of patients with and without OI.²⁶ In the authors' experience at large centers treating many hundreds of patients with OI, there is no evidence that patients with OI have an increased risk of malignant hyperthermia, and the trend toward mildly increased baseline body temperature should be recognized with care taken to avoid overwarming.²⁶ Of particular interest to the surgical team is a variable level of coagulopathy that has been reported in with OI, which may result in greater-than-anticipated surgical blood loss.²⁷⁻²⁹ Approximately two-thirds of patients will report easy bruising, which is likely multifactorial and due in part to capillary fragility and impaired platelet aggregation.³⁰ While prolonged bleeding times are uncommon, preoperative coagulation testing may be of benefit prior to undertaking major surgical procedures such as spinal deformity correction.

While increasing proportions of patients with OI are being treated with bisphosphonate medications, the optimal perioperative administration of these medications is unknown. Animal studies have suggested that bisphosphonate medications may delay the process of long bone fracture healing,^{31,32} however, there are scant clinical data in patients with OI to guide clinical decision making. Munns et al. undertook a retrospective logistic regression analysis of patients with OI who sustained a lower limb fracture or underwent a surgical osteotomy to determine whether pamidronate therapy had a differential effect on healing rates.³³ The authors found that improved mobility was the most significant factor associated with nonunion after 12 months in both groups. Osteotomy remained independently associated with nonunion after adjusting for mobility status, but fracture did not, suggesting that osteotomies had lesser healing potential than fractures, or were more preferentially affected by pamidronate therapy. Older patient age and osteotomy of the tibia were also found to be independently associated with nonunion. Given the concern for impaired bony healing, it is our preference to withhold bisphosphonate treatment prior to a planned spinal fusion; however, current data is insufficient to form a definitive recommendation on whether or not bisphosphonate medications should be held, and, if so, for what duration. The decision to continue bisphosphonate medications perioperatively must be made on an individual basis in collaboration with the patient's medical or endocrine physicians after weighing the reduction



Figs. 24.3A to F: Halo gravity traction for gradual thoracolumbar deformity correction followed by posterior spinal fusion in a patient with Sillence type III osteogenesis imperfecta.

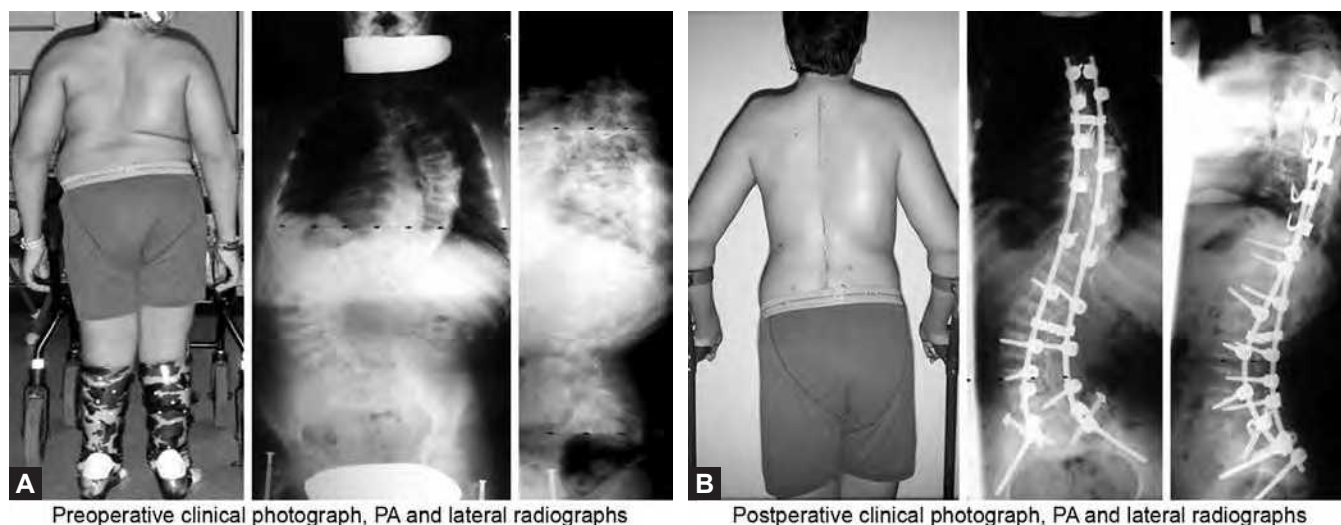
in fracture risk and improved comfort with scheduled bisphosphonate treatment versus the potential for increased time to spinal fusion.

NATURAL HISTORY OF SPINAL MANIFESTATIONS

While OI affects the entire body, its effects on the axial skeleton are especially morbid and difficult to treat. Abnormalities have been reported at all levels of the spine, including deformity of the craniocervical junction, cervical kyphosis, thoracic kyphoscoliosis, lumbar hyperlordosis, spondylolisthesis, and sacropelvic dysmorphism. An understanding of the natural history of these conditions is essential prior to considering surgical intervention, which may present additional technical challenges specific to the disease process.

The calvarial bones are frequently thin and fragile in OI. Skull malformations may be avoided in some children with early medical treatment and careful change of position in infancy to avoid prolonged compression fractures on one segment of the skull, in the authors' experience. Thinning of the calvarial bones has implications for treatment of spinal disease, particularly with regard to the use of halo gravity traction. This necessitates the use of multiple pins (typically 8 or more), and the pins should only be finger-tightened. The pins must be monitored closely, as the authors have observed complications including skull fracture, pin penetration, or even skull elongation, during halo gravity traction in patients with OI.

Radiographic abnormalities of the craniocervical junction are commonly observed in OI. While these are most often asymptomatic, progressive deformity may result in compression of the cervical spinal cord and brainstem,



Figs. 24.4A and B: Posterior spinal fusion for progressive thoracolumbar kyphoscoliosis and spondylolisthesis in a patient with Sillence type IV osteogenesis imperfecta.

resulting in syringomyelia, hydrocephalus, seizure activity, or death.^{34,35} Neurologic manifestations are variable, and may also include headache, ataxia, apnea, quadriplegia, lower cranial nerve palsy, dysphagia, nystagmus or hyper-reflexia.³⁶ Sillence et al. initially described a prevalence of 25% for craniocervical abnormalities, with neurologic involvement from basilar impression most common in patients with OI type IVB.³⁷ A more recent cross-sectional study by Arponen et al. found a prevalence of 37% in their series of 76 patients with Sillence types I, III, and IV OI.³⁸ These were grouped into three types: platybasia (flattening of the anterior cranial base angle), basilar impression, and basilar invagination. Importantly, 44% of affected patients were noted to have multiple abnormalities. Kovero et al. reported rates of platybasia, basilar impression, and basilar invagination of 11.1%, 35.2%, and 22.2% respectively in their series of 54 patients with OI.³⁹ Cheung et al. identified the patient's height Z-score as the single most important independent predictor of craniocervical involvement in asymptomatic patients with OI.⁴⁰ No significant correlation was found with other putative factors, such as age, gender, blue sclerae, lumbar spine bone mineral density, or underlying genotype. In addition, no association was identified with prior bisphosphonate use, suggesting that bisphosphonates are not protective against progressive craniocervical junction deformity. While less commonly observed, myelopathy or tetraparesis has been described secondary to severe cervical kyphosis in OI.^{41,42}

Thoracic kyphoscoliosis is the most common spinal finding in OI, and it is a frequent indication for surgical

intervention (Figs. 24.4A and B). Manifestations are variable, but a predominance of thoracic kyphosis is characteristic.⁴³ Curve progression is often rapid, most likely due to ligamentous hyperlaxity and cumulative insufficiency fractures of the vertebrae and rib cage. These factors also conspire to limit the efficacy of bracing, which is largely unable to prevent truncal shortening and may ultimately worsen thoracic deformity and pulmonary function.^{11,29,44,45} The presence of numerous biconcave vertebral bodies has been reported in patients with more severe congenital variants of OI, and it is associated with the development of scoliotic curves $>50^\circ$ but not necessarily of thoracic kyphosis.^{46,47} However, Englebert et al. observed that scoliosis typically precedes the onset of pathologic kyphosis. The authors also noted that earlier achievement of antigravity and motor milestones was associated with delayed onset of spinal deformity.¹³ Watanabe et al. demonstrated a correlation between Z-scores of bone mineral density and body mass index with scoliotic curve Cobb angles in OI.⁴⁸ Indeed, thoracic curves with Cobb angles of $>60^\circ$ have been found to be strongly associated with decreased vital capacity and self-reported physical health component scores in OI.¹² These findings reinforce the role of systemic medical treatment for bone mineral density in order to prevent curve progression and potential respiratory compromise, though this has not yet been definitively demonstrated given the relatively limited cumulative experience with bisphosphonate treatment in these patients.

Maintenance of sagittal balance is essential for ambulation and sitting, and regional sagittal plane deformity

may result in compensatory curve progression. As such, it is difficult to separate the etiologies of such findings in OI as lumbar scoliosis or hyperlordosis, spondylolisthesis, and pelvic obliquity or dysmorphism. Abelin et al. performed a quantitative analysis of sagittal alignment in a cohort of patients with OI compared to healthy controls.⁴³ The authors observed a significant increase in upper thoracic kyphosis in the OI group without compensatory lumbar lordosis, resulting in anterior offset of the thorax. In the absence of increased lumbar lordosis, such changes mandate retroversion of the pelvis to maintain global sagittal balance. This may subsequently prevent ambulation in patients with concomitant hip flexion contractures.⁴⁹ There are multiple reports of a potential association between bony fragility and spondylolysis in OI,⁵⁰⁻⁵² though Verra et al. initially observed pars defects in only 5.3% of patients with OI; a rate similar to that of the general population.⁵³ More recently, Hatz et al. reported an 8.2% rate of spondylolysis occurring at an average age of 7.5 years in their review of 110 ambulatory patients with OI.⁵⁴ The authors also reported spondylolisthesis in 10.9% of patients occurring at an average age of 6.5 years. Spondylolisthesis in OI may be either isthmic or dysplastic in nature, as high-grade multilevel spondylolisthesis may be seen in association with severe pedicle elongation and lumbar hyperlordosis in the absence of pars defects.^{55,56}

SURGICAL INDICATIONS AND CLINICAL OUTCOMES

Fractures occurring with minimal trauma are a hallmark of OI. While not as common as those affecting the appendicular skeleton, fractures of the spine are an important source of morbidity in OI and may necessitate surgical intervention in rare cases. The vast majority of spinal fractures are compression fractures of the thoracolumbar vertebral bodies that may be relatively occult, and their accumulation may contribute to spinal deformity. In the absence of severe pain, deformity, or neurologic involvement, nonsurgical management is preferred in most cases. While these fractures may have an atypical radiographic appearance, the familiar anatomic approach to determining whether injury patterns are stable or unstable is useful in determining whether surgical intervention is warranted. Special consideration must be given to the impact of ligamentous laxity, if present, on the competence of the posterior ligamentous complex in the absence of obvious bony injury. Compression fractures may also be seen in the

cervical spine, as highlighted by Leng et al.⁵⁷ The authors reviewed two representative cases in neurologically intact patients, illustrating their decision for nonsurgical management of a stable injury versus circumferential fusion for an unstable injury with progressive deformity despite bracing. Similar principles apply to management of other cervical spinal injuries, as patients with OI typically have normal fracture healing potential despite baseline fragility. Indeed, there are multiple reports of successful nonsurgical management of traumatic spondylolisthesis of C2 with collar immobilization in patients with OI.⁵⁸⁻⁶⁰ A high index of suspicion for spinal injury must be maintained in any patient with OI who has abnormal neurologic findings, even without a history of trauma. Ziv et al. reported a case of paraplegia with sensory sparing from bilateral pedicle fractures and cervical spondyloptosis after a low-energy fall and subsequent chiropractic manipulation.⁶¹ The authors chose halo traction followed by anterior decompression via costotransversectomy and staged noninstrumented long posterior fusion with good postoperative recovery of neurologic function.

Given the similarity of compression fractures in OI to those commonly observed due to osteoporosis, many have sought to apply vertebroplasty and kyphoplasty techniques to this patient population in order to alleviate pain and prevent progressive deformity. Vertebroplasty in OI was first reported by Vasconcelos et al., who made a technical note of transient intraoperative hypotension without evidence of cement embolism, paralleling the experience of cement use in arthroplasty.⁶² Rami et al. first reported long-term clinical follow-up on one case of percutaneous vertebroplasty at T10 in a patient with OI, noting complete resolution of pain at 1 week postoperatively that endured throughout the 17-month follow-up period.⁶³ Tozzi et al. also reported a case of vertebroplasty in OI that was remarkable for intravenous cement embolization that necessitated a successful open pulmonary embolectomy.⁶⁴ While not unique to OI, concern exists regarding the higher potential for fractures adjacent to those treated by cement augmentation. Indeed, Kaso et al. noted adjacent-level fracture after a fall in a patient with OI who had just undergone vertebroplasty.⁶⁵ The authors treated this fracture as well with vertebroplasty and bracing and reported a good eventual clinical outcome at 11 months postoperatively. Long-standing OI frequently results in distorted bony anatomy, often making it difficult to discern pre-existing from acute deformity and increasing the complexity of typical surgical exposures and percutaneous

access routes. However, the severity of osteoporosis in OI may actually be exploited for the purposes of percutaneous access to the lower lumbar spine, as a transiliac trajectory to the L5 pedicle has been successfully reported for L5 vertebroplasty in a 66-year-old patient with OI.⁶⁶ Recent interest in kyphoplasty as a means to potentially reduce post-traumatic kyphosis has led to its application in OI as well. Hardenbrook et al. reported on the use of kyphoplasty in combination with silicate-substituted calcium phosphate in a young patient with OI and multiple-level compression fractures.⁶⁷ This treatment option theoretically allows for biologic restoration of more physiologic bone density in OI, thereby reducing the risk of adjacent-level fracture, though no long-term data are available to confirm its efficacy for this application. Successful use of cement as a bone void filler following kyphoplasty in OI has also been reported, with good relief of pain and no adjacent fractures over 9 months of follow-up.⁶⁸ While such case reports are encouraging, it is important to note that vertebroplasty and kyphoplasty in OI remain experimental techniques, as there is insufficient evidence to make a systematic assessment of their safety and efficacy in this patient population.

A feared and potentially lethal consequence of OI is progressive craniocervical deformity leading to compression of the spinal cord and brainstem at the foramen magnum. A variety of surgical approaches have been described to address this complex problem. Initial surgical efforts consisted of posterior suboccipital and cervical indirect decompression; however, posterior decompression alone was associated with recurrence of symptoms and the need for subsequent occipitocervical fusion.^{34,69,70} Harkey et al. reviewed their early experience treating eight cases of basilar impression with neurologic involvement, in which they advocated for primary anterior transoral decompression followed by staged posterior occipitocervical fusion.⁷¹ The authors reported the use of a LeFort I midface osteotomy to improve anterior exposure when necessary. Up to 2 weeks without skeletal traction elapsed between stages. Six of eight patients experienced long-term neurologic recovery with one death in the perioperative period from complications of bronchopneumonia and sepsis prompting eventual withdrawal of care. Sawin and Menezes subsequently reviewed their series of 25 patients with osteochondrodysplasias (18 with OI) undergoing surgical intervention for craniocervical abnormalities.³⁶ An algorithmic approach to treatment was proposed, with asymptomatic patients first undergoing bracing with a

Minerva-type orthosis. The development of symptomatic hydrocephalus prompted ventriculoperitoneal shunt placement. Deformity progression despite brace immobilization or development of symptomatic anterior neural compression prompted a trial of cervical traction. The authors distinguished between deformity that was reducible or irreducible with traction, performing posterior-only decompression and fusion for reducible cases, and staged anterior decompression with posterior fusion for irreducible cases. Patients undergoing fusion were placed in halo or orthotic immobilization for a mean duration of 8.2 months postoperatively until radiographic evidence of bony union was noted. Importantly, in the twelve patients undergoing halo immobilization, only one superficial pin-site infection was encountered, with no complications due to fragility of the calvarial bones. Good to excellent results were reported in 22 of 25 patients over the mean follow-up period of 5.9 years. Anterior approaches with transoral-transpalatopharyngeal exposures are technically formidable, requiring a multidisciplinary surgical team and sophisticated perioperative care. As a result, others have advocated for gradual preoperative reduction, with or without halo traction, followed by posterior decompression and occipitocervical fusion.⁷²⁻⁷⁵ While such results are encouraging for patients with reducible deformity, the poor quality of the bone formed in OI does not guarantee that successful posterior fusion alone is sufficient to prevent recurrent anterior compression or hydrocephalus. The long-term outcomes of combined anterior decompression and posterior stabilization were reassessed by Ibrahim et al., who examined cases occurring over a 21-year period with a median 10-year follow-up period.⁷⁶ The combined approach demonstrated optimal outcomes in patients with higher preoperative functional scores, as well as largely durable relief of neurologic symptoms over the follow-up period in patients who experienced immediate postoperative improvement. All patients underwent elective tracheostomy and gastrostomy placement to facilitate the anterior extended maxillectomy and recovery period. Despite these precautions, high rates of complications were observed, including respiratory infection, dysphagia, nasal speech, surgical wound infection, and depression. The extensive morbidity and prolonged hospital course associated with this highly invasive procedure has motivated the development of endoscopic techniques for anterior decompression. Applying techniques applied for decompression of cervicomedullary rheumatoid disease, Hansen et al. reported a case of endoscopic transnasal

resection of the clivus, anterior arch of the atlas, and odontoid tip in a patient with OI and symptomatic basilar invagination.⁷⁷ The patient was repositioned and a posterior occipitocervical fusion was subsequently performed. Endoscopic techniques have the potential to spare the patient considerable morbidity associated with an open transoral or transmaxillary approach, but these are technically challenging and require the use of intraoperative image-guided navigation. Menezes more recently reviewed his 20-year experience with treatment of craniocervical abnormalities in osteochondrodysplasias, including 28 patients with OI.⁷⁸ While the treatment approach evolved over time, he noted the later relative success of bracing with a custom Minerva-type occipitocervical orthosis, along with nighttime cervical collar traction as needed, in preventing craniocervical deformity progression as assessed by yearly magnetic resonance imaging (MRI). This may be most effective during early adolescence, when the rate of symptomatic deformity progression was noted to be highest. Hydrocephalus was assessed independently and treated by ventriculoperitoneal shunt placement when necessary. This treatment protocol was successful in preventing the need for anterior transoral decompression with posterior fusion in all but approximately 20% of patients with OI and related osteochondrodysplasias.

For the patient with symptomatic craniocervical compression, we recommend an initial trial period of halo gravity traction under strict neurologic surveillance, followed by repeat imaging with computed tomography and MRI. If a satisfactory reduction is achieved, an *in situ* instrumented posterior occipitocervical fusion may then be performed. Anterior approaches are considered only for cases refractory to indirect reduction techniques, as the morbidity and associated complications as noted previously are significant. These factors and expected outcomes must be carefully discussed with the patient and family prior to surgical planning. In addition to craniocervical junction abnormalities, deformity of the subaxial cervical spine is a rare but challenging manifestation of OI. Daivajna et al. described a case of myelopathy due to progressive cervical kyphosis that developed despite a prior posterior cervical fusion.⁴² Due to the distorted anatomy and head position, the authors report use of an anterolateral approach with a Y-shaped incision to gain exposure for corpectomies and cage reconstruction.

Thoracolumbar kyphoscoliosis is another spinal manifestation of OI that may have severe morbidity and remains challenging to treat despite advances in spinal instrumentation. Early literature on spinal deformity in OI was

primarily descriptive, with few early reports of Harrington instrumentation and posterior fusion for deformity correction.⁴¹ Cristofaro et al. were among the first to systematically report results from a series of 49 patients with OI.⁷⁹ Of these, 35 had some form of spinal deformity, and eight ultimately underwent surgical correction. A combination of preoperative traction, Harrington instrumentation, and noninstrumented techniques were used, with postoperative bracing in all cases. The authors emphasized that significant deformity correction was not achievable, and that the primary goal of surgery was stabilization *in situ*. Pre- and postoperative functional status was largely conserved, and no loss of correction or pseudarthrosis was seen over 9–12 months of follow-up. Benson et al. were also early advocates of operative intervention for spinal deformity in OI, reporting on an early series of 12 patients undergoing instrumented and noninstrumented posterior fusions.¹¹ The authors used cement augmentation of the hook sites, and observed a slight advantage in subsequent deformity correction with the use of instrumentation. Yong-Hing and MacEwen undertook a survey of the Scoliosis Research Society membership, gathering data on 121 patients with OI and spinal deformity treated by bracing, surgery, or both.²⁹ Sixty of these patients underwent surgical intervention; 55 had a posterior, four had an anterior, and one had a combined anterior/posterior fusion. The mean age at which surgical correction was performed was 15.6 years. The authors again noted more durable correction with instrumentation; however, they also detailed the numerous technical complications associated with its use. These included intra- or postoperative hook cutout, rod breakage, and sacral bar migration. One or more perioperative complications were present in 16 of 39 patients undergoing instrumented fusions, versus 2 of 16 without instrumentation. Hanscom et al. published a radiographic classification of OI based on data from a series of 64 patients.⁴⁵ The classification incorporated data from the appearance of the long bones, vertebral bodies, pelvis, and ribs, and it was applied to the 43 patients in the series with spinal deformities to assess prognostic value. Curve progression was not uniform in patients with type A disease (a mild variant with bowing of the long bones in relative isolation) but was near-universal in types B through E. Of these patients, 13 ultimately underwent surgical intervention. Instrumentation was used in 12 of 13 cases, beginning with Harrington compression-distraction rods but reflecting a trend toward increasing use of segmental Luque-Galveston techniques over time. Casting or bracing was used for 6–9 months postoperatively.

Of note, the authors observed gradual loss of correction over the follow-up period in several patients despite radiographic evidence of a solid fusion mass. They concur with prior authors' recommendations for considering early surgical intervention for curves between 40° and 50°, as more rapid progression has been observed after this threshold.⁸⁰ In addition, the amount of correction obtainable in OI is severely limited by poor bony fixation. To address this concern, the use of preoperative halo gravity traction has been employed in order to achieve gradual correction facilitating a subsequent *in situ* fusion. Gitelis et al. reported use of the technique, followed by staged anterior and posterior instrumentation with cement augmentation, for scoliosis correction in OI.⁸¹ Janus et al. subsequently described in detail a series of 20 consecutive patients with OI and scoliosis treated with preoperative halo gravity traction.⁸² The authors noted migration of the halo when six pins were used according to their standard protocol, prompting an increase in the number of halo pins to ten. With this fixation, traction of up to one-half body weight was possible for a mean period of 90 days. Once serial radiographs showed no further evidence of curve correction with traction, posterior *in situ* fusion was performed with Cotrel-Dubousset pediatric instrumentation in 18 patients, or Harrington instrumentation in 2 patients. Halo and orthosis use was continued postoperatively. The authors report obtaining additional iliac crest bone grafts from close relatives of the patients immediately prior to surgery when required. Mean pretreatment, immediate preoperative, and postoperative coronal plane Cobb angles were 78°, 53°, and 51°, respectively. The mean scoliosis correction achieved with traction was 25° (32%); this decreased to 19° (25%) over the follow-up period. Mean pretreatment, immediate preoperative, and final follow-up sagittal plane Cobb angles were 56°, 42.5°, and 44°, respectively. Mean kyphosis correction from pretreatment to final follow-up was 12° (21%). Improvements in ambulatory capacity were noted in 7 of 20 patients; no patients experienced a decrease in functional status following surgery. The authors acknowledge that the use of preoperative traction is controversial and concede that it is difficult to attribute their results to the use of traction, modern segmental instrumentation, or both. However, they conclude that preoperative halo gravity traction was generally well-tolerated, is particularly suited to correction of spinal deformity in OI due to the combination of ligamentous laxity and poor bone quality and propose that it may facilitate conditioning and rehabilitation in the

perioperative period. Tolboom et al. undertook a detailed assessment of functional outcomes and patient-perceived competence in a series of 11 patients with OI undergoing spinal fusion for scoliosis correction.⁸³ Long constructs from T2 to L5 were created in all except for one case in which thoracic fusion alone was performed. A posterior approach with Luque instrumentation was used in 7 cases and Cotrel-Dubousset instrumentation in 3 cases. An anterior approach was used in one patient. Mean preoperative and postoperative coronal plane Cobb angles were 55° and 39°, respectively, yielding a mean correction of 20° (36%). Additional outcome measures included a validated six-component self-competence scale obtained pre- and postoperatively in all patients. No significant changes were observed in functional capacity and ambulatory status at final follow-up. Trends toward significant improvements were seen in several of the other outcome measures, but only self-reported scholastic competence was found to demonstrate a statistically significant increase over the follow-up period. Four patients required additional surgery—one for deep infection and three for proximal junctional kyphosis. The authors conclude that surgical intervention for scoliosis in OI has no deleterious effects on function and may result in improvements perceived self-competence. They note that the patients in their series were not undergoing bisphosphonate treatment and postulate that this may help prevent curve progression in both the pre- and postoperative states.

It is important to consider the impact of spondylolisthesis, if present, when addressing sagittal plane deformity in OI. Hanscom et al. reported three patients with coexistent scoliosis and spondylolisthesis in their series, and the fusion construct was extended to the sacrum in one patient with a grade III spondylolisthesis.⁴⁵ Spondylolisthesis has also been reported inferior to the fusion construct following deformity correction in OI,⁸⁴ and the impact of increased bony fragility must be considered when selecting the end vertebrae of a long fusion. Basu et al. reported two cases of spondylolisthesis due to pars elongation in association with thoracic scoliosis in OI.⁵⁵ The authors treated one case of progressive spondylolisthesis and lumbar hyperlordosis with a retroperitoneal approach and noninstrumented anterior fusion from L3 to the sacrum using tricortical interbody bone grafts. The patient was placed in a plaster cast for 3 months, followed by orthosis immobilization for an additional 3 months. Successful fusion was noted, but progression of thoracic scoliosis prompted combined anterior/posterior fusion from T1

to L1 at 18 months following the lumbar fusion. Ivo et al. reported three cases of spondylolisthesis in OI, also due to pars elongation.⁵⁶ One patient underwent surgical intervention for severe elongation of pedicles L2 to L5 and a preoperative L3 to S1 sagittal Cobb angle of 136°. The authors chose a posterior approach with a laminectomy and posterolateral fusion using Cotrel-Dubousset instrumentation. The distorted anatomy of the pedicles resulted in partially extrapedicular screw placement. Slight postoperative improvement in lumbar pain was noted, with successful fusion and no further progression of the lumbar deformity. Of note, instrumentation prominence and pressure sore formation necessitated gradual removal of the instrumentation over 6 years following surgery. Ambulatory capacity was preserved until eventually limited by progressive pelvic deformity and acetabular protrusio.

TECHNICAL CONSIDERATIONS

Surgical intervention in OI presents a number of unique challenges to the surgeon. When considering the fundamental roles of decompression or stabilization in spinal intervention, several principles emerge that may guide the treatment approach. Realistic goals and careful preoperative planning with attention to these principles can help ensure positive outcomes and minimize the occurrence of complications. The approach must be careful and meticulous to minimize bleeding given the variable coagulopathy often encountered in OI. Exposure of the spine in a sequential fashion may aid in decreasing blood loss. We recommend the use of predominantly monopolar cautery, and the Cobb elevator must be used with caution so as not to fracture the posterior lamina.

The limitations of bone quality in OI cannot be overstated. In severe cases, the bone is of such abnormal consistency that it may be cut with a blade similar to other soft tissues. In general, acute intraoperative reduction or deformity correction is to be avoided whenever possible in favor of gradual preoperative correction. The ligamentous laxity frequently observed in OI helps facilitate this approach. Halo gravity traction is a useful technique for gradual correction of craniocervical or thoracolumbar deformities, but it requires maximizing the number of pin sites and close observation to prevent complications. Following traction, the goal of surgery subsequently becomes decompression, decortication, and placement of bone graft and/or substitutes to facilitate fusion with minimal or no correction obtained intraoperatively. Distorted

anatomy or concerns about pelvic fracture propagation often limit the amount of available bone graft for long fusion constructs, though the spinal pathology may be so severe as to warrant the extensive use of autograft for its superior healing potential despite these risks. If required, banked allograft bone or other bone substitutes may be used to augment the available allograft. Obtaining biologic fixation and expediting bony fusion is especially important in OI, as instrumentation is prone to early pullout or failure. Circumferential fusion with bone graft is preferable where possible, as this provides additional protection against curve progression that may occur even with a healed posterolateral fusion.

The improved fixation obtainable with the use of modern segmental instrumentation has allowed for additional correction, earlier mobilization, and lesser reliance on external casting or bracing postoperatively. Despite these benefits, there are many circumstances where the extensive use of pedicle screws is not feasible or may be detrimental. Distorted pedicle anatomy, as in dysplastic spondylolisthesis, may not provide a sufficient bony conduit for screw placement. Typical techniques for screw placement using the pedicle probe or awl are inadvisable and must be replaced by drilling techniques (either with the hand drill or powered oscillating drill; in some cases a 2.5-mm drill must be used). To achieve safe drilling, at least on the concavity and apex of the curve, we recommend direct exposure of the medial wall of the pedicle through a small laminotomy. While trying to insert a pedicle screw, one must always remember that this may result in the fracture of the pedicle and a loss of fixation. Adult patients with severe OI and scoliosis are frequently of small stature, and may necessitate the use of pediatric instrumentation (5.0- or 5.5-mm rods, 4.0-mm screws). Dilation of small or sclerotic pedicles to accommodate even pediatric pedicle screws may not be possible without resulting in a fracture. At such levels, sublaminar wires or tapes may be used, as it is preferable to achieve some form of fixation at every possible level rather than forgoing fixation at levels not amenable to screw placement. Sublaminar wires or hooks may even be used to supplement intact pedicle screws as needed. To augment screw fixation, polymethylmethacrylate bone cement may be used in two different ways: either by injection of the cement into the screw hole followed by pedicle screw insertion, or by embedding the heads of the implants in cement. The latter technique is especially useful at the proximal and distal aspects of the construct.

CONCLUSION

Osteogenesis imperfecta is a disorder of collagen synthesis with wide-ranging skeletal manifestations. Because of the incredibly diverse nature of the OI population and the variable severity of the disorder, each patient must be evaluated as thoroughly as possible for bone structure, bone quality and density, and associated soft tissue abnormalities. Spinal pathology occurring in OI may be significantly morbid and especially difficult to treat. A number of surgical strategies have been described to address abnormalities of the craniocervical junction, insufficiency fractures, and thoracolumbar spinal deformity. Surgical intervention in OI remains technically challenging, though new methods and instrumentation continue to result in improved outcomes. Awareness of established techniques and treatment principles in OI may help guide surgical decision making and prevent complications. At present, the effect of medical management with bisphosphonates on the incidence and progression of spinal deformity has not been adequately studied. Early experience suggests that bisphosphonate therapy may result in better surgical fixation and possible improved correction of deformity, though it remains unclear if this will improve long-term maintenance of correction or result in increased rates of pseudarthrosis.

LEARNING OBJECTIVES

- Recognize the spinal manifestations of osteogenesis imperfecta (OI)
- Identify the impact of associated spinal deformity on overall health and quality of life in patients with OI
- Understand specific technical considerations related to spinal surgery in patients with OI.

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Scheuermann's Disease

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Snapshot

- » Clinical Aspects
- » Imaging

- » Treatment

INTRODUCTION

Scheuermann's disease is named after the radiologist Holger Scheuermann, who first described the characteristic lesions of watchmakers' apprentices in 1920.¹ His initial hypothesis was that the disease was caused by aseptic necrosis of the ring apophysis of the vertebra (the cartilaginous plate surrounding the vertebral nuclei which give rise to secondary ossification). However, this theory was reassessed following the works of EM Bick and JW Copel² who demonstrated that the apophysis plays no role in growth and necrosis has never been observed. The most recent histological studies have shown that the collagen content of the vertebral endplates is relatively low³ and explains the growth disorder. It is therefore a primary and not a secondary ossification disease.

Scheuermann's disease or juvenile kyphosis or juvenile osteochondrosis of the spine are one and the same disease resulting in pathological kyphosis in adolescents caused by damage to the vertebral bodies. The exact pathophysiological cause of the disease has not been clearly established, but autosomal dominant familial forms indicate genetic involvement. Factors associated with the disease include male gender, obesity and tallness, but their exact role is unknown. Microtrauma and sporting activities are more debatable factors.

CLINICAL ASPECTS

Scheuermann's disease is a relatively common disease observed in both its clinical and radiological form and its

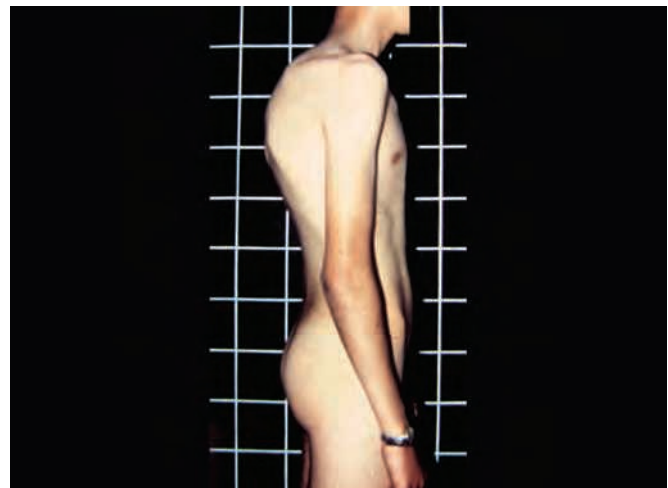


Fig. 25.1: Clinical presentation of “upper” Scheuermann's disease.

asymptomatic form (50–60% of adolescents are affected when vertebral plate irregularity is used as a radiological definition) (Figs. 25.1 and 25.2).

Typically, it is observed in boys of 15–16 years of age (earlier in girls) who consult either for spinal pain or for accentuated thoracic kyphosis. However, the disease may also be diagnosed following routine examinations. The pain is generally moderate but may be absent; it is mechanical in nature and most often transient. Kyphosis is the alarm sign for parents, general practitioners and school physicians. It appears progressively and is not particularly incapacitating for the patient.

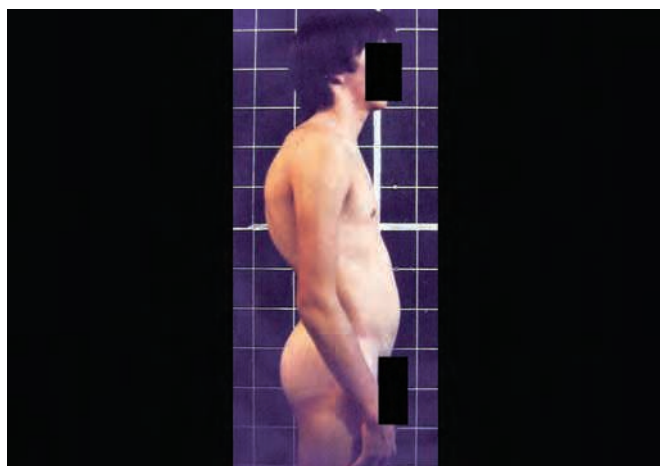


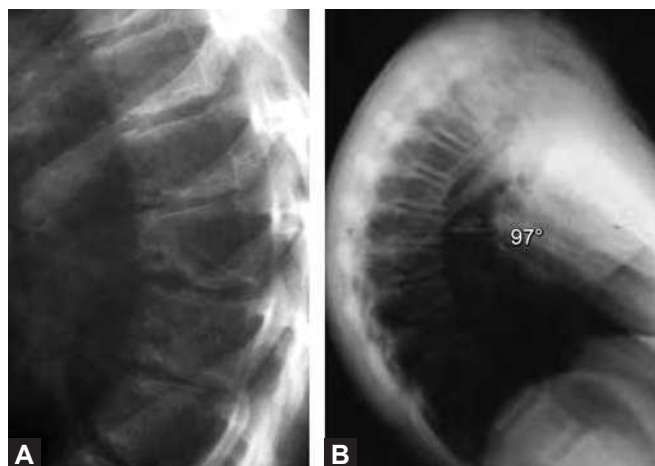
Fig. 25.2: Clinical presentation of “lower” Scheuermann's disease.

A physical examination in the standing position (see Fig. 25.1) and then lying down permits an assessment of the degree of kyphosis and its correctability. The plumb line test is used to evaluate the distance between the apex of the kyphosis, the spinous process of C7, the spinous process of L3 and the upper part of the intergluteal cleft (equivalent to S2). This test is useful for patient follow-up. The examiner must assess the mobility of the vertebral column and examine the patient for gibbosity, which is usually minimal, but may indicate a slight rotation of the vertebral column. Examination in the dorsal and ventral recumbent positions is used to assess the correctability of the curvature.

The clinical signs of Knutsson⁴ and Edgren and Vainio⁵ are practically pathognomonic because they point to disharmonic growth.

Finally, the clinical examination should include gathering information for differential diagnosis. An in-depth neurological examination should be performed, but the results thereof are usually normal. The presence of any neurological sign rules out Scheuermann's disease, though anterior compression of the spinal cord has been encountered in rare cases. It should be noted, however, that vibratory pallesthesia and abnormal proprioception associated with slight motor dysfunction but no tendon reflex abnormalities are observed in 15% of cases.⁶ Secondary sexual characteristics should be noted in order to assess the child's development. The purpose of the examination is to eliminate secondary kyphosis and to assess the localization and degree of kyphosis, essential for long-term development and choice of a treatment strategy (Fig. 25.2).

The Murray study,⁶ a prospective study that included 67 patients with a mean kyphosis angle of 71°, contributed



Figs. 25.3A and B: (A) Typical appearance of vertebral bodies in Scheuermann's disease layered, irregular appearance of the vertebral endplates and wedging; (B) important kyphosis of 97°.

to a better understanding of the long-term development of the disease. The study involved clinical, radiological and respiratory assessments over a mean period of 32 years. The results were compared with those of a control group of 32 patients. The study patients suffered more lumbar pain, were more likely to have sedentary jobs and less spine extension mobility. They did not seem any way impaired in their daily activities or bothered by cosmetic appearance. Furthermore, no respiratory function disorders were found in patients presenting with a kyphosis angle of <90°. Those with a kyphosis angle >90° had restrictive lung disease. However, since only a few low-power epidemiological studies have been performed, no hasty conclusions should be drawn regarding disease-related complications, or on the awkwardness patients may feel about their appearance over the long term; but they should be taken into account when deciding on a treatment strategy from the range of available options.

IMAGING

The paraclinical assessment should comprise front and profile images of the patient in the standing position. Images should include the occiput and femoral heads to allow for analysis of spinal and pelvic sagittal balance parameters. The low radiation imaging system EOS (EOS Imaging Paris, France) provides the most reproducible measures. Assessment of bone age using the Greulich and Pyle method based on a single X-ray of the left hand or elbow is useful for evaluating spine maturation, as is Risser's sign.⁷

Typical radiological findings (Figs. 25.3A and B) include irregular vertebral endplates, which appear to be layered

(a flaky pastry aspect) with blunted anterior edges, disc space narrowing and multiple herniations of the nucleus pulposus associated with wedging of the vertebral bodies. Several radiological definitions exist for Scheuermann's disease and the first of these was established by Sorensen in 1964.⁸ His definition of the radiological criterion for diagnosis of Scheuermann's disease was wedging of 5° or more in at least three consecutive vertebrae. As for Bradford,⁹ the criteria include irregular vertebral endplates, loss of intervertebral disc space, wedging of at least one vertebral body and hyperkyphosis of >40°. However, there are several forms of the disease that do not comply with these definitions and whose signs are on the threshold between normal and pathological. There is no clear consensus among authors on the definition of pathological kyphosis: values range between 12° and 57° for Stagnara,¹⁰ between 20° and 40° for Roat, while for Bradford,⁹ it must not exceed 40°.

TREATMENT

Scheuermann's disease may be treated in a number of ways. Treatment should always be initiated with conservative methods that should be instituted as early as possible.

Conservative treatment is based on three approaches: hygiene and diet, physiotherapy and bracing.

Hygiene-dietary rules should be applied from the youngest age, with the prohibition of all passive vertical positioning of children with immature and defective vertebral columns. The child's standing and sitting positions must then be regulated, as should all its physical activities. The patient's position may be regulated by use of adapted school and home furniture, and by suitable physical exercise, i.e. stretching exercises that reinforce the muscles of the posterior vertebral column, and by avoiding postures that increase the kyphosis. Sports must remain recreational and all notion of competition should be forbidden.

Physiotherapy is essential for the management of Scheuermann's disease. For optimal results, the vertebral column must still be partially flexible and correctable. The efficacy of treatment is very dependent on the motivation of the patient and of the physiotherapist. The aim of treatment of postural abnormalities with spinal and pelvic imbalance is chiefly to reinforce the tone of the erector muscles of the spine, to stretch the contracted muscles and the curvatures. Furthermore, physiotherapy helps the patient understand the orthopedic treatment protocol, which is often difficult to endure.

An important aspect of conservative treatment involves the use of orthotic devices to stop disease progression,



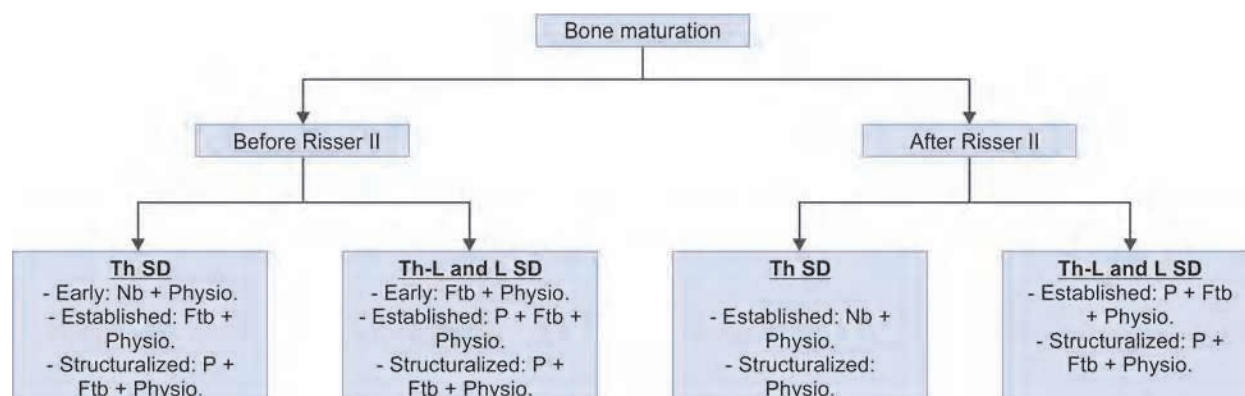
Fig. 25.4: Milwaukee-type brace.

reconstruct, rebalance and correct sagittal abnormalities. This very restrictive treatment often leads to major patient resistance, which makes it essential that patients and their families adhere to the treatment project. Young patients with early disease may be treated with a Milwaukee-type brace providing median posterior support (Fig. 25.4).

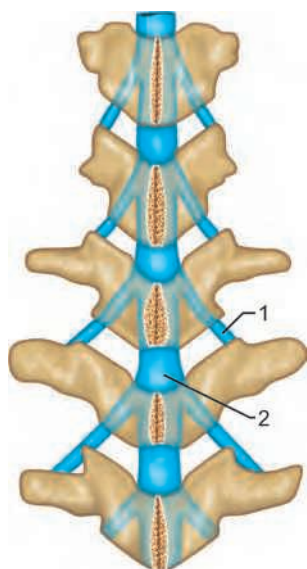
Many active-passive and passive braces have been described for the more severe forms of the disease. They generally comprise a posterior pad and two anterior pads. It is often necessary to start treatment by using the elongation-derotation-flexion casting technique to improve flexion of the vertebral column. The duration and modalities of treatment with braces have not been clearly codified. This conservative treatment is generally disappointing in the long term. Its main purpose is to stop the disease progression and prevent the development of a more severe form of the disease and to avoid surgery. Conservative treatment is rarely curative and is most effective when applied to young subjects. Garreau de Loubresse has established a decision tree for orthopedic management based on bone maturation (whether Risser's sign II has been reached or not), localization of the lesions (thoracic, thoracolumbar or lumbar) and on the stage of disease progression (early, established, structuralized) (Flowchart 25.1).¹¹

Surgery is an option for severe forms of the disease.

The methods used for surgical correction have been perfectly defined. They are all based on spinal fusion (arthrodesis) with anterior, posterior or circumflex autogenous grafting, associated with posterior segmental compression instrumentation to straighten the spine. There is still no consensus as to whether posterior or combined anteroposterior procedures are better.

Flowchart 25.1: Decision tree. Treatment strategy for Scheuermann's disease (SD).

(Physio: Physiotherapy; Nb: Night-time brace; Ftb: Fulltime brace; P: Plaster; Th SD: Thoracic SD; Th-L SD: Thoracolumbar SD; L SD: Lumbar SD).

**Fig. 25.5:** Ponte osteotomy.

The length of the spinal segment fused is also an important parameter. Long fusion (10–12 vertebrae on average) enables a better load distribution. The major risk associated with short fusion is postoperative angle loss and the appearance of over- or underlying junctional kyphosis, as in the series of Pejin et al.¹² Many authors consider that it is reasonable not to correct the initial curve by >50%, or the patient may suffer major neurological complications.

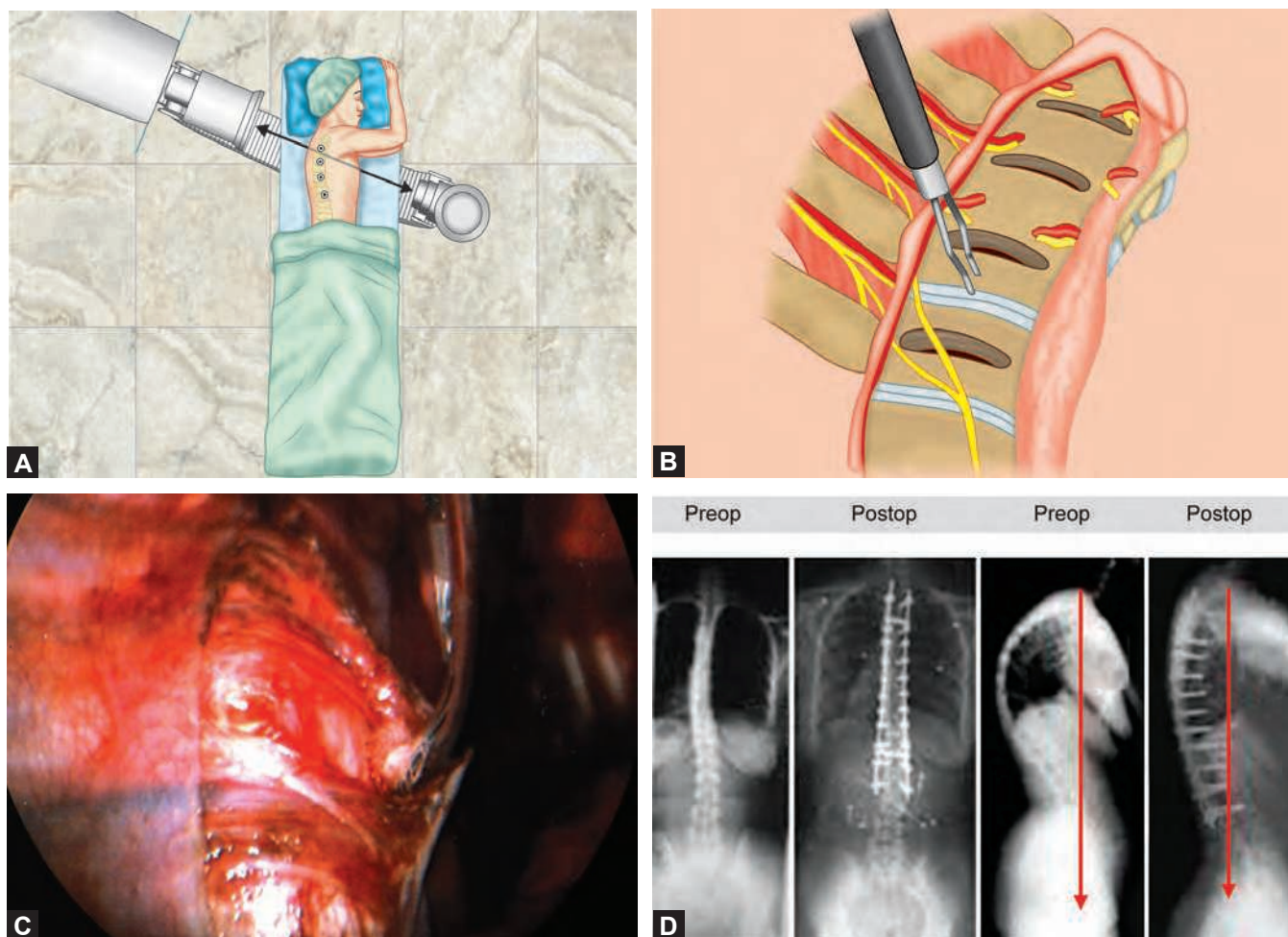
We recommend the Ponte posterior-only procedure (Fig. 25.5). It consists in bilateral resection of the posterior facets, also removing the isthmus, which produces

effective posterior compression provided that the disc maintains a certain amount of anterior flexibility. If the anterior disc opening is too wide, additional intersomatic grafting is recommended. In such cases, the procedure should be carried out by thoracoscopy. Where the anterior discs are very stiff, they must first be released by thoracoscopy (Figs. 25.6A to D) or by thoracotomy before the posterior procedure is performed, with or without Ponte osteotomy, but always with pedicle screw instrumentation and postoperative bracing.

Surgery for the treatment of Scheuermann's disease must only be used exceptionally in adolescents. Not only the significance of the deformity but also the complications associated with surgery⁹ and the good tolerability of balanced kyphosis must be taken into account. The use of intraoperative evoked potentials is essential to secure this corrective procedure, which may put the anterior spinal artery under pressure.

CONCLUSION

Scheuermann's disease is a juvenile kyphosis secondary to vertebral disc pressure and overload. Its impact is variable in adults and depends on where the lesions are located and whether or not the kyphosis is balanced. The shortcomings of treatment protocols, which only treat the sequelae, must be taken into account in the overall long-term management of patients. Screening and preventive management are of primordial importance in this disease.



Figs. 25.6A to D: (A) Positioning; (B) anterior release; (C) perioperative view of anterior release and grafting by thoracoscopy, and (D) postoperative control after posterior correction.

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Spinal Deformity in Familial Dysautonomia

Eiman Shafa, Suken A Shah

Snapshot

- » Epidemiology and Genetics
- » Neuropathology
- » Clinical Presentation and Diagnosis
- » Orthopedic Manifestations
- » Management of Spinal Deformity
- » Postoperative Concerns
- » Prognosis

INTRODUCTION

Familial dysautonomia (FD), first described in 1949 and termed Riley-Day syndrome,¹ is a rare genetic disorder with extensive autonomic and small-fiber sensory dysfunction. The condition is most aptly classified in the larger scheme of rare neurodevelopmental disorders labeled *hereditary sensory and autonomic neuropathies* (HSANs). It is defined as HSAN type III and distinguished from other HSANs by unique pathogenetics and predominant central and peripheral autonomic involvement. There are five reported HSANs of which FD is the most common, best studied, and remains of particular orthopedic interest due to prevalence of skeletal deformity in this population. The disorder's nonorthopedic concerns also present a unique challenge in the surgical and nonsurgical management of these patients.

EPIDEMIOLOGY AND GENETICS

There have been nearly 600 registered patients worldwide since 1970,² and are almost exclusively of Ashkenazi, or Eastern European, Jewish descent.^{3,4} Familial dysautonomia is transmitted in an autosomal recessive mode of inheritance with an estimated prevalence of one in 3,600 live births and a carrier rate of 1:27 to 1:36 among the Ashkenazim.^{3,5,6} One study identified a significantly higher carrier rate (1:18) among Ashkenazim of full Polish

background compared to non-Polish counterparts (1:99) suggesting the need for focused population screening.⁴ Males and females are affected equally. Notably, other HSANs do not share this well-defined ethnic bias.

The genetic defect has been mapped to the distal long arm of chromosome 9 (9q31-q33).^{3,7} A single noncoding, base-change mutation in gene *IKBKAP* (IkB kinase-associated protein) has been shown to be responsible for >99.5% of all reported FD cases.⁶ The mutation causes decreased splicing efficiency and a variable *IKBKAP* message. This produces an abnormally truncated IKAP protein product of the human elongation complex.^{3,7-9} Though initially believed to play a critical role in transcription, IKAP is now known to have a wide array of roles including histone acetylation, tRNA modification, and regulation of cell-surface transport.¹⁰ Two other very rare pathological FD gene mutations have been identified in heterozygous carriers. Both mutations are believed to disrupt phosphorylation.³

Despite the presence of homozygous *IKBKAP* mutation in this recessive disease, cells from patients with FD are capable of expressing wild-type *IKBKAP* message and associated elongator protein complex. The predominant mutation pattern in FD, hence, results in variable expression of the gene in a tissue-specific manner. Brain and nervous tissue from individuals with FD expresses primarily mutant *IKBKAP* mRNA, while fibroblast and

lymphoblast cell lines express predominantly the wild-type *IKBKAP* message. The molecular basis of this finding is yet unknown, but the discrepancy does suggest that neuronal cells are particularly intolerant of compensating for the missplicing.^{3,8,11}

■ NEUROPATHOLOGY

Familial dysautonomia is a progressive neurological disease with characteristic neuropathological findings that provide the structural basis for the biological and clinical manifestations of the disease. Though central, peripheral, and autonomic neurons are affected, much of our understanding is based on peripheral findings from nerve biopsies. Sural nerve biopsies have been classically used for tissue diagnosis. These findings illustrate incomplete neuronal development and limited survival of autonomic and sensory neurons leading to progressive neuronal degeneration.^{3,12,13} Sympathetic development is affected more significantly than parasympathetic.^{3,14} The greatest impact is seen on small, unmyelinated nerve fibers that mediate autonomic function and carry pain, temperature, and taste sensation. Larger myelinated afferent nerve fibers may also be deficient, including those that relay impulses from muscle spindles and Golgi tendon organs. This results in a decreased number of unmyelinated and small myelinated fibers leading to the broad clinical manifestation of autonomic dysfunction. Significant variability may exist in the presentation of this disease from patient to patient and over time. In fact, neuronal depletion in the dorsal root ganglia and spinal cord correlates well with the clinical progression of disease with age.³

Central nervous system dysfunction remains clinically apparent in individuals with FD, but thus far poorly defined without consistent qualitative anomalies found. However, more recent genetic studies do show altered expression of normal gene product in the central regions consistent with clinical evidence of central autonomic dysfunction.¹⁴

■ CLINICAL PRESENTATION AND DIAGNOSIS

The resultant multisystem dysfunction of FD is present at birth. Despite significant variability in expression, the diagnosis of FD is suspected clinically based on appreciation of five fairly consistent “cardinal” criteria: absence of overflow tears with emotional crying (alacrima), depressed patellar deep tendon reflex, decreased taste and absence

of lingual fungiform papillae, lack of axon flare with intra-dermal histamine, and documented Ashkenazi Jewish extraction.³ However, diagnosis can be definitively established by molecular genetic testing of *IKBKAP* in questionable cases.

In infancy, poor suckling and esophageal dysmotility can lead to stubborn feeding difficulties, aspiration pneumonia and eventually chronic lung disease. Relative insensitivity to hypoxia and vomiting crises can compound these issues. Due to vasomotor lability, infants often show signs of hyperhydrosis, temperature dysregulation, and blotchy erythema which in turn can be a source of significant physical and emotional stress. “Autonomic crises” are triggered due to stress, which manifest in 40% of individuals with FD sometime after 3 years of age. Crises refer to attacks of cyclical vomiting lasting 24–72 hours that are associated with hypertension, profuse sweating, apprehension and irritability. Breath-holding spells, leading to syncope, are also rather characteristic of FD in the first 5 years of life. Though no associated mortality has been reported, breath-holding spells do present significant risk for trauma and fractures.

Later in childhood, sensory ailments become more pronounced and orthopedic concerns become more apparent. Relative indifference to pain leads to corneal ulcerations, tongue maceration, self-injury, and accidental trauma leading to multiple, often unrecognized, fractures and avascular necrosis. In general, young patients with FD are hypotonic that may be due to a combination of central deficits and decreased tone from stretch receptors.⁹ Walking is expectedly delayed and appears ataxic due to poor sensory feedback from muscle spindle cells as well as vestibular nerve dysfunction. Speech is likewise mildly delayed and often characterized as nasal and slurred due to dysarthria.

Severe orthostatic hypotension without compensatory tachycardia is characteristic and due to decreased sympathetic vascular innervations. This does significantly limit the mobility and function of the adult patient. Episodic supine hypertension is a centrally driven finding that is less well understood. Inappropriate release of central catecholamines and exaggerated peripheral response due to denervation hypersensitivity is believed to be the etiology. Further manifestation includes bradycardia and cardiac arrhythmia often requiring pacemaker placement. Body temperature dysregulation is also a rather common presenting as hypothermia or severe fever. This, along with breath-holding-related hypoxia, has been linked to a major motor seizure disorder in FD.

Emotional lability is a prominent feature of FD. These episodes can lead to or intensify during autonomic crises. Treatment with benzodiazepines has been well documented. Most individuals are of low, normal intelligence but able to participate in their medical care.

■ ORTHOPEDIC MANIFESTATIONS

Orthopedic problems are common in FD and cause significant disability.^{15,16} Consistent musculoskeletal manifestations of FD include delayed walking, delayed puberty and short stature, ataxia, foot deformities, tibial torsion, osteochondritis, avascular necrosis, neuropathic joint deformity, osteopenia or osteoporosis due to gastrointestinal dysfunction, joint contracture, increased incidence of fractures, and most commonly spinal deformity.^{9,15,17,18}

Decreased pain perception, unsteady gait and lack of reflexive protective movements significantly increase the risk of inadvertent trauma. In a review of 182 FD patients, Laplaza et al. found that 60% of patients had one or more fractures at a rate of 1.4 fractures per patient, which was significantly higher than their healthy counterparts. Most commonly involved bones were the radius, tibia, and femur with a peculiarly high rate of proximal femur fractures in this population. Neuropathic joints manifested in 11% though believed to be an underestimation.⁹ The knee was the most frequently involved joint followed by the foot-ankle and hip.

Spinal Deformity

Spinal deformity is the most prevalent musculoskeletal problem in FD with a reported incidence ranging from 50% to 95% in surviving dysautonomia patients.^{16,17,19-21} Since no bony cause has been identified as the root of deformity progression, it is possible that focal demyelination in the ascending posterior columns of the spinal cord, thoracic nerve roots, and spinocerebellar tracts results in proprioceptive and kinesthetic changes.¹⁶

Scoliosis is the most common deformity pattern; however, there is a significant predilection for kyphosis in the FD population.¹⁹⁻²² The apex of kyphotic deformity is usually quite cephalad with 90% proximal to the fifth thoracic vertebra.²¹ Scoliosis is defined as $>10^\circ$ of coronal plane curvature and thoracic kyphosis is defined as sagittal plane curvature $>40^\circ$. Larger studies did not find a significant difference in prevalence between males and females.^{15,19}

Spinal deformity presents early in life and many cases are diagnosed prior to 2 years of age.¹⁷ Hayek et al. found that scoliosis and kyphosis were diagnosed on average at 8 and 9 years of age, respectively. At presentation, curve magnitudes of 60% of patients were rated as severe and only 18% rated as mild. And, unlike idiopathic scoliosis in which a majority of curves are the apex right thoracic and the apex left lumbar, 40% of FD patients present with left-sided thoracic curves.¹⁹ No means of predicting curve progression has yet been established, but curves progress during the adolescent growth spurt. Growth velocity is accelerated by growth hormone therapy used for management of short stature.²³

Reported curve characteristics vary widely with scoliosis seen in 25–56%, kyphoscoliosis seen in 25–73%, and pure kyphotic deformity seen in 2–4%.^{15,19,20} The curve pattern of scoliosis is also highly variable. Bar-On et al. found that the majority of patients have a single thoracic or thoracolumbar curve, while 35% had a double curve. Thoracic hyperkyphosis is more common in patients with a double major curve.¹⁵

■ MANAGEMENT OF SPINAL DEFORMITY

Conservative Management

Nonoperative treatment of spinal deformity has proven to be challenging, poorly tolerated and fraught with frequent complications. Despite this, most patients are initially treated in a custom orthosis. Bracing is often initiated around 10 years of age and continued for 3–4 years.¹⁵

Patients with FD have significant emotional lability that makes enforcing brace wear particularly difficult for the patients' families. The physical and emotional stress associated with this process can in fact be the trigger to autonomic crises. Approximately 40% of patients have a history of autonomic crises as discussed above. Additionally, relative thermal instability may also be troublesome with bracing and body casting leading to hyperthermia that has been linked to seizures in patients with FD.¹⁶ Patients should be monitored for euthermia and air conditioning used for elevated body temperatures.

Other than wear tolerance and poor compliance, brace-associated pressure ulceration is also common in the setting of decreased sensation and relative pain indifference. Frequent skin checks and regular brace fitting are important preventative measures. As kyphosis is a common component of spinal deformity in FD, the Milwaukee

brace had been classically prescribed; however, bivalve thermoplastic thoracolumbosacral orthoses are now more often used and somewhat better tolerated by patients.^{16,17,20} Bracing is also associated with decreased ability to exercise and a progressive increase in muscle weakness attributable to their disease, activity avoidance, and frequent respiratory infections.¹⁶ Others have noted increased rate of gastroesophageal reflux and aspiration pneumonias due to recumbent positioning and nightly gastrostomy feeds leading to their recommendation to discontinue overnight bracing.¹⁹

Albanese et al., in an early report on treatment results, reported brace intolerance in all of their patients.¹⁷ Hayek et al. found that despite bracing, 89% of curves progressed with thoracic and lumbar curve progression of 5° and 4° per year, respectively. Interestingly, they found association between curve magnitude and the change that occurred during bracing.¹⁹ Kaplan et al. found similar coronal plane curve progression but reported kyphosis to deteriorate at a rate of 9° per year.²⁰

Physical therapy has been shown to be effective as adjunctive management in milder curves.²⁴ Exercises and modalities should be individualized to address the patient's specific issues given the variability of disease presentation. Exercise, compression stockings, and increased fluid and salt intake help prevent symptomatic orthostatic hypotension. Focused occupational therapy to enhance oropharyngeal coordination may allow better feeding and help the patient's nutritional status and decrease aspiration risk drastically. Breathing exercises and regular respiratory therapy should begin at an early age to prevent recurrent pulmonary pneumonia. Musculoskeletal focus of physical therapy revolves around increased flexibility of the spine, core strengthening, gait training and postural exercises. To address kyphotic deformity, further exercises focus on strengthening the erector spinae, hyperextension exercises, and pectoralis stretching.²⁴ Electrical muscle stimulation has been used as adjunctive therapy, but lacks clinical support.

Surgical Management

The need for early treatment of spinal deformity in progressive neurological disorders was first recognized by Hensinger and MacEwen, who reported on the surgical management of a limited cohort.²⁵ However, multisystem involvement, a host of serious medical problems, and the risk of perioperative mortality in individuals with FD make surgical optimization, planning, and deformity correction

challenging. Still, surgical management is advantageous compared to observation or conservative measures if attempted at an early stage in the evolution of progressive spinal deformity.

In general, surgical management of scoliosis and kyphosis is indicated for curve magnitudes >40° and >65°, respectively, in patients who failed conservative management.¹⁵ However, attempts are made to delay arthrodesis until adolescence, as patients with FD are characteristically of short stature. Usually, a relatively short fusion is indicated and can serve to prevent further loss of stature due to progressive deformity. For severe deformity with cardiopulmonary compromise on initial presentation, it is not unreasonable to work toward operative management as the index procedure. The decision is further influenced by the patient's overall health and the readiness of their family.

Preoperative workup consists of liver, lung, and renal function testing, as well as electrolyte and nutritional assessment. Surgery should be done in a period free on frequent pulmonary infection and when the patient's family is free of other distractions or burden. In essence, a multidisciplinary team familiar with dysautonomia should work to optimize the patient.

On the day of the operation, it is important to maintain adequate hydration and avoid patient overstimulation and anxiety; anxiolytics are often required. Because of poor oral intake, chronic dehydration and prerenal azotemia are common in this population. These patients are admitted the day before surgery, since intravenous fluid resuscitation for 12 hours prior to anesthesia is recommended.²⁶ Because of increased aspiration risk, cimetidine has been used prior to anesthesia to reduce gastric secretions. Given the patient's relative insensitivity to hypoxia and hypercapnia, premedication with narcotics is avoided.

Intraoperative concerns include an autonomic crisis and cardiovascular collapse. Experienced anesthesia teams can avoid this with proper preparation, hydration, maintenance of intravascular volume, and blood replacement. Posterior spinal arthrodesis is preferred over anterior approach surgery to avoid postoperative pulmonary complications secondary to the transpleural surgical approach. Hybrid or third generation (all pedicle screw) instrumentation can be used, but osteopenia may challenge the strength of the bone-implant interface and the senior author has also employed sublaminar wires or cables to augment correction forces along with pedicle screws. Postoperatively, consideration can be given to

bracing patients to protect the spinal implants, but this is poorly tolerated for reasons described above.

Rubery et al. and Bar-On et al. reported on their series of surgical curve corrections. Scoliosis was reduced by 36–40% compared to the preoperative curve, but at longer follow-up only 18–20% reduction was maintained. The authors noted failure proximal and distal to the fusion. Kyphotic deformity was reduced by 12–20%, but at longer follow-up only 3–4% correction was maintained. Both studies found that the loss of correction in kyphosis occurred only proximal to the instrumented arthrodesis. Rubery et al. hypothesized that due to existing rigid cervical lordosis, patients develop sagittal imbalance following posterior thoracic fusion leading to proximal junctional failure and implant pullout. They addressed this by extending the fusion far cephalad in the thoracic segment and adding a cervical extension to the postoperative orthosis. Henderson et al. provided radiographic evidence to support this hypothesis by showing a 50% reduction of intervertebral flexion–extension excursions at all cervical levels other than C1–C2 in the FD population compared to normal values. C1–C2 excursion was 20% below normal values.²²

Kaplan et al. reported that all of their patients treated surgically, and the preoperative ataxia improved considerably and rapidly. These patients also had decreased rate of hospitalizations for pulmonary infections following surgery.²⁰

POSTOPERATIVE CONCERNS

Surgical management of spinal deformity in FD is met with frequent postoperative complications. Most common of these involved the skin, respiratory, and gastrointestinal systems.²¹ The most common single complication is pneumonia that can lead to generalized sepsis or extended intensive care stays. Failed fixation in the form of screw pullout, implant breakage, and hook disengagement has been reported by multiple authors. Bar-On et al. found curve progression at the site of arthrodesis in association only with instrumentation failure. Pseudoarthrosis is rare in this population, and despite all-posterior fusion in a relatively young population, no crankshaft phenomenon is reported.²⁰ Cyclical crisis patterns may arise with sufficient stress in any affected individual with FD in the perioperative period. Stress can be emotional due to anxiety or physiological due to infection, postoperative pain, visceral pain from constipation, sleep deprivation, or fatigue.

Despite a myriad of postoperative concerns and complications, reported surgical mortality is low in several larger studies.^{15,20,21}

PROGNOSIS

Patient survival and quality of life have significantly improved in the past 50 years.¹⁰ With greater research across multiple disciplines and an established patient registry, we now know far more about the disorder and the care of individuals with FD. Prior to 1960, only 50% survival past 5 years of age was predicted, though today 50% of FD patients live beyond 40 years of age.³ This drastic improvement in life expectancy is in part due to early treatment of spinal deformity and enhanced respiratory care resulting in far fewer deaths due to pulmonary complications.

Sands et al. showed that young adults with FD reported both mental and physical quality of life within the average range and that their self-esteem improved with age.²⁷ Individuals with FD have married and had families, living far more productive lives than before.

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SECTION

3

Metabolic Disorders

S Rajasekaran



Nonoperative and Operative Management of Paget's Disease

Ganesh Swamy, Kenneth Thomas

Snapshot

- » Epidemiology
- » Etiology/Pathophysiology
- » Clinical Manifestations
- » Diagnosis
- » Treatment
- » Case Presentation

EPIDEMIOLOGY

Paget's disease of bone (PDB), also known as osteitis deformans, is the second most common metabolic bone disease after osteoporosis.^{1,2} Paget's disease of bone was first described by English surgeon Sir James Paget (1814–1899).³ Paget's disease of bone is characterized by enlarged weakened bones that may lead to deformity, fracture, and pain. Paget's disease of bone has a predilection for the axial skeleton.⁴ Paget's disease of bone prevalence varies across human races and locations. In the United Kingdom, the overall prevalence of PDB is estimated to be 2–3.7%^{1,5–7} but occurs rarely in China, Japan, Middle East, India, and Scandinavia.^{8,9} In a South African study, the prevalence of PDB was 1.3% in blacks and 2.4% in whites.¹⁰ Paget's disease of bone is most prevalent not only in the United Kingdom and Western Europe but also in those with British ancestry in Australia, New Zealand, South Africa, North America, and South America.¹¹ A radiographic study from the United States suggested that the prevalence of disease was 1–2% with near equal rates among blacks/whites and sexes.¹² Others have found a slightly higher incidence in males.^{7,12} The risk of PDB increases with age, going from 2% prevalence at age >50 to a 6–10% prevalence at the age of 90 or greater.^{7,13}

There is evidence to suggest that the prevalence of PDB is declining over time^{7,14,15} and that the disease severity is also diminishing.¹⁶ The prevalence of PDB in Britain in

1994 was only 40% of that noted in a prevalence study from 1974, suggesting a possible environmental etiology to this disorder.⁷ Several groups have noted an almost 50% reduction in age and sex-adjusted incidence in the 20 years after initial reports in the 1980s.^{14,16,17} Further, they noted that plasma alkaline phosphatase (ALP) at diagnosis, disease extent on scintiscan, and the numbers of bones involved were diminishing over time.¹⁶

Paget's disease of bone has been identified to be somewhat heritable. Siris et al. found a positive family history in parents or siblings in 12.3% of patients with PDB and only 2.1% of controls. Alternatively said, the rate of Paget's disease was six times higher in relatives of cases than in relatives of controls.¹⁸

Paget's disease of bone can be thought of as being either monostotic or polyostotic, with >60% of cases being polyostotic.^{1,19,20} Monostotic forms affecting the spine are rare, although with the declining severity of disease monostotic spine disease may become more apparent. The spine is the second most common site of involvement for PDB,^{6,21–27} following the pelvis.^{23,27,28} Overall, 35–53% of patients with PDB have spinal involvement.^{20,29,30}

ETIOLOGY/PATHOPHYSIOLOGY

The etiopathology of PDB is an exciting knowledge area, with much new information arising in recent years that has allowed for both genetic and molecular understanding of

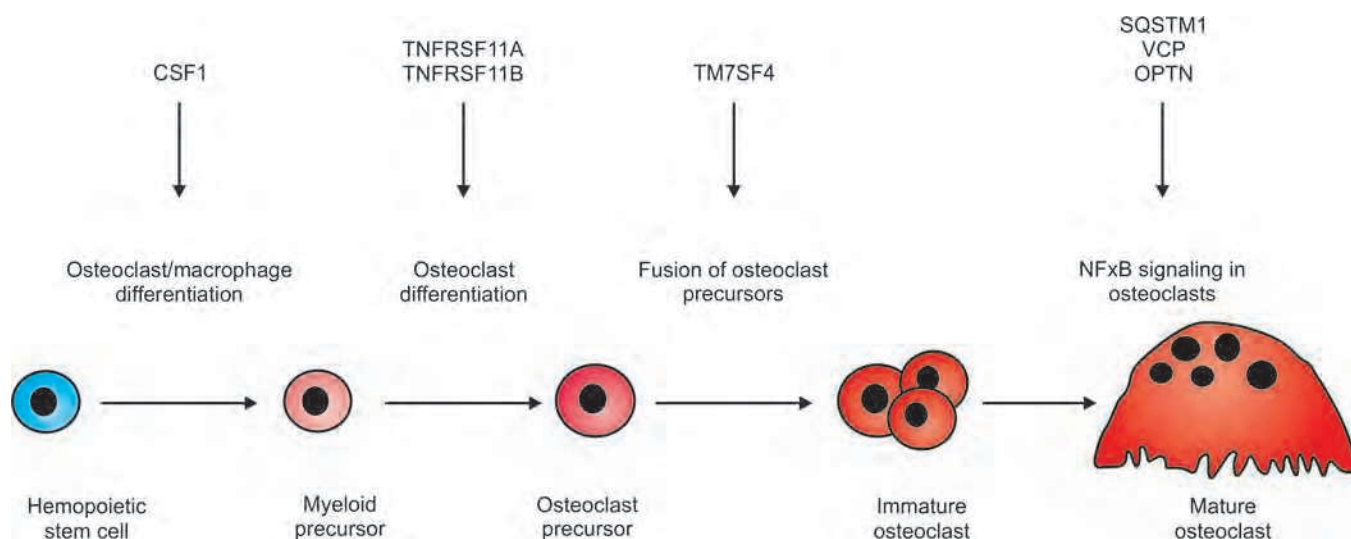


Fig. 27.1: Genes that predispose to PDB play key roles in osteoclast differentiation and function. The CSF1 gene encodes macrophage colony-stimulating factor, which is essential for osteoclast and macrophage differentiation. The TNFRSF11A and TNFRSF11B genes encode RANK and OPG, respectively, both of which play critical roles in osteoclast differentiation and function. The TM7SF4 gene is required for fusion of osteoclast precursors. The SQSTM1, VCP, and OPTN genes all play key roles in the regulation of NFκB signalling and autophagy.

classic histopathological findings. Pagetic bone arises from rapid osteoclastic activity, with subsequent haphazard bone formation, described as a mosaic admixture of woven and lamellar bone and seen particularly well with polarized light.^{5,31} Paget's disease of bone is typically hypervascular, with late marrow fibrosis.^{5,32} Vertebral involvement results in increased bone density, trabecular volume, and vertebral size.^{31,33}

The cellular characteristics of PDB are very different from normal bone, with many fold increases in both osteoclasts and osteoblasts.³¹ Paget's disease of bone is primarily felt to be a disease of osteoclasts that differ from normal by having larger size, being highly multinucleated, and having inclusion bodies.^{34,35}

Classically, PDB has been described in temporal phases with an initial lytic phase, where osteoclastic activity predominates and mimics hyperparathyroidism, leading to an increased ALP.⁶ A mixed phase of osteoblastic repair and ongoing lytic activity follows, with the last pathologic phase consisting of a decrease in bone activity.⁶

While most PDB cases are spontaneously acquired, about 12–15% of cases are familial, passed in an autosomal dominant pattern linked to chromosome 18.^{36,37} Genetic linkage analysis in multiple affected populations has led to an association with sequestosome 1 (SQSTM1/p62);^{38,39} 40–50% of familial PDBs carry mutations of this gene as do 10% of sporadic cases.³⁶ SQSTM1/p62 is felt to be an adaptor protein to *TNF receptor-associated factor*

6, bringing together parts of the RANK/RANKL (receptor activator of nuclear factor-κB ligand) signaling cascade,⁴⁰ which undergoes missense or nonsense mutations in PDB. SQSTM1 mutations, when combined with other genetic markers, may predict the severity and extent of PDB in patients, raising the prospect of personalized risk assessment and early treatment.⁴¹

The central role of the osteoclast in PDB is reinforced through recent genome-wide association studies, identifying several osteoclast maturational and functional genes with relatively large effect sizes.⁴¹ Ralston has illustrated the location of these genes along the osteoclast maturation pathway (Fig. 27.1).⁴²

The presence of inclusion bodies in Pagetic osteoclasts has led to suggestions of the role of Epstein-Barr virus, canine distemper virus, or measles virus (MV) in PDB. Clinical data regarding viral causation are mixed, with reports differing on whether or not viruses can be found, and if so, whether contamination led to the diagnosis.^{42,43} Mouse models of MV proteins overexpressed in osteoclast precursors do seem to create PDB lesions, perhaps underscoring the relevance of the viral theory.⁴⁴

CLINICAL MANIFESTATIONS

Paget's disease of bone may be asymptomatic or alternatively result in pain, deformity, and fracture. Low back pain (LBP) is a common complaint with a prevalence of 27%.²²

Table 27.1: Causes of low back pain.*Causes*

Periosteal stretching
 Vascular engorgement
 Microfractures
 Facet arthritis
 Intervertebral disc disease
 Overt fractures
 Spondylolysis/lithesis
 Sarcoma(rare)

Controversy exists as to whether the LBP is due to PDB primarily or due to degenerative changes. Hadjipavlou found that of those patients with back pain 24% had pain due to PDB alone (pain unrelated to activity and not relieved with rest), 50% due to degenerative changes, and 26% due to a combination of PDB and degenerative changes.⁸ However, Altman et al. have attributed LBP in PDB patients to coexisting osteoarthritis in 88% of cases.^{12,45} Specific causes of LBP in the PDB patient are summarized in Table 27.1.¹

When the spine is affected by PDB secondary neurological symptoms may be present, due to spinal stenosis, in approximately one third of patients. Bony compression by expanding Pagetic bone is thought to be the most common cause of spinal stenosis,²⁴ although other numerous pathological processes have been implicated, including fractures and vascular steal.⁸

The lumbar spine is the most common region of spinal involvement—affected in 58–62% of patients, followed by thoracic spine with cervical spine involvement forming the minority of cases.^{30,31} Involvement of the atlantoaxial region is rare. Lumbar stenosis may lead to radiculopathy and/or neurogenic claudication. When cervical or thoracic disease is present, the resultant stenosis may lead to radiculopathy and/or myelopathy. Myelopathy is more commonly related to thoracic lesions,⁴⁶ likely because of the smaller cross-sectional area of the spinal canal as compared to the cervical region.

Complications related to PDB include pathological fracture and malignant transformation. Spontaneous spinal epidural hematoma, complicating spinal involvement of PDB, has also been reported rarely.⁴⁷ The majority of pathological compression fractures occur in the lumbar spine.⁴⁸ Malignant transformation of PDB is a rare and dreaded complication. In a study of 1,078 asymptomatic and symptomatic patients, eight cases of malignant transformation were identified, yielding an overall incidence of

Table 27.2: Diagnostic imaging features.Plain radiographic features⁵¹

- Vertebral body expansion
- Trabecular thickening
- Picture frame sign (dense peripheral vertebral body with lucent vertebral center)
- Ivory vertebrae (sclerotic phase)
- Ghost vertebrae (rare presentation in lytic phase)

CT features⁵¹

- Periosteal apposition
- Endosteal apposition/resorption

MRI features⁵¹

- Marrow infiltration
- Apparent epidural fat ossification
- Spinal stenosis
- Facet joint hypertrophy

(CT: Computed tomography; MRI: Magnetic resonance imaging).

0.7%.⁴⁹ The estimated incidence of Paget sarcoma in those patients with symptomatic PDB is 2–4%.²⁹ Sharma et al. identified 89 patients with secondary sarcoma due to PDB affecting the spine from the Scottish Tumor Registry over a 59-year period. Thirteen cases were available for review. Mean age of these 13 patients was 67 years. There was a preponderance of males and sacral spine involvement. Back pain was the most common presenting feature. Seventy-seven percent of cases were of osteosarcoma. Mean survival of all 13 patients was 4.2 months, unchanged throughout the almost 60-year study period.

DIAGNOSIS

Differential diagnosis of PDB includes metastatic disease, hematopoietic malignancy, metabolic bone disease, primary tumor, and infection. Plain radiographs, computed tomography (CT), and magnetic resonance imaging (MRI) are useful imaging modalities in the diagnosis of PDB. The diagnosis can usually be made by plain radiography.⁵⁰ Characteristic imaging features are summarized in Table 27.2.

Serum ALP is elevated in ~80% of untreated patients with PDB.^{11,50} Serum ALP reflects the severity and extent of disease and therefore may be normal in less active monostotic disease. Serum calcium and phosphorous are usually normal. Asymptomatic patients may be diagnosed with PDB when blood work or radiographs are ordered for unrelated reasons. If there is uncertainty regarding the

diagnosis based on imaging and laboratory studies, a biopsy may be performed to reveal typical Pagetoid histopathology.

Bone scans can be very useful in distinguishing between monostotic and polyostotic forms of the disease. While they can be useful in monitoring response to treatment, the fact that bone scan changes are correlated with serum markers obviates the need for follow-up scans.⁵²

TREATMENT

The treatment of PDB, even when it involves the spine, is first medical. While the indication for a PDB patient's presentation to a spine surgeon's office can vary from pain to neurologic dysfunction, treatment should always begin addressing the underlying pathology. Even if surgery is anticipated, medical treatment can decrease bleeding complications and even improve neurology.⁵³

Medical treatment primarily consists of bisphosphonate treatment. Efficacy of treatment can be monitored with markers of bone formation [serum ALP and N-terminal propeptide of type 1 collagen (P1NP)], and markers of bone resorption (C- and N-terminal telopeptides of type 1 collagen—CTX and NTX).⁵⁴ One can anticipate normalization of ALP levels in 60–90% of patients within 2 months, with subsequent improvement in radiographic and histological parameters.⁵⁴

Initial experience suggested oral treatment for a period of 60 days, with a relapse rate of up to 40% at 2 years.⁵⁵ A short course of treatment potentially avoids bisphosphonate-related complications, such as osteonecrosis of the jaw.^{56,57} Subsequently, a randomized-controlled trial comparing zoledronic acid (5 mg administered intravenously once) versus risedronate (30 mg daily for 60 days) surprisingly showed superior results for the one-time treatment.⁵⁸ Even more, longer term results suggested that biochemical markers remain normal in 99% of zoledronic acid-treated patients, and 87.5% of zoledronic acid patients had clinical success at the late time-point 6.5 years after diagnosis, raising the possibility of cure in PDB.⁵²

Other medications to be contemplated in the medical management include analgesics, nonsteroidal anti-inflammatory drugs, and antineuropathic medications, as dictated by the clinical scenario.³⁶ The RANKL inhibitor denosumab can also be used instead of bisphosphonates when impaired renal function is encountered.⁵⁹

Spinal neurological compressive symptoms are seen and thought to be primarily due to circumferential bony compression. However, a vascular steal syndrome can

also be seen, due to the hypervascularity of the bone, and presumed shunting of some of the spinal cord blood supply.^{60,61} The vascular steal was initially recognized when PDB patients present with neurological signs and normal myelograms, which then responded to calcitonin treatment.^{61,62} Steal phenomenon was then invoked to explain neurological dysfunction after successful decompression or from PDB vertebral fractures. Neurology can improve, after medical management, even without drastic improvement in the imaging findings.⁶³

If medical treatment fails due to a lack of response, or perhaps when the neurological deficit is severe, surgery should be offered. Patients may present acutely with fractures through PDB areas. They are often elderly, harboring other medical comorbidities, with newly diagnosed PDB. Transpedicular biopsy may be necessary to confirm diagnosis, if imaging is not diagnostic. Less invasive techniques, such as laminectomy and kyphoplasty, can be used.^{8,64,65} If spine surgery is anticipated, cardiac function must be evaluated as PDB can cause left ventricular hypertrophy and dysfunction due to a high output cardiac adaptation to increased blood flow.⁶⁶ Cell salvage techniques are also recommended, as Pagetoid bone may bleed profusely.⁵³

CASE PRESENTATION

A 64-year-old man was referred to the outpatient spine clinic with a history of weakness and paresthesias affecting both arms. These symptoms were present and gradually progressed over 4 years. For the previous 4 months, he had difficulty with his hand writing and performing most fine motor tasks. He had a Trendelenburg gait on the right and had been using a cane.

Past medical history included PDB diagnosed in 1989 after right hip fracture that was treated with open reduction and internal fixation. He was not taking any medications. He was operating a hobby farm in his retirement.

He used a cane in his left hand. Without his cane, his gait was unsteady. Tandem gait was not possible. The patient had brisk deep tendon reflexes throughout his upper and lower extremities. He had no Hoffmann reflexes and an equivocal Babinski response but did have sustained ankle clonus bilaterally. His motor power was intact with the exception of the right arm. He had Grade 4 out of 5 weakness throughout the right C5-T1 myotomes. Sensory perception to light touch was intact throughout.

Radiographs of the pelvis revealed end-stage changes related to PDB affecting the pelvis and right femur more



Fig. 27.2: Anteroposterior pelvis depicting widespread cortical thickening, bilateral fusion of the SI joints, deformity of the right femur, and severe bilateral hip arthritis secondary to polyostotic PDB (SI: Sacroiliac; PDB: Paget's disease of bone).



Fig. 27.3: Lateral X-ray lumbar spine: L5/S1 is fused, anterior to posterior enlargement of L4, "picture frame" appearance of L2.



Fig. 27.4: Lateral radiograph: increased density of C2, C3, and C4, anterior-to-posterior vertebral expansion at C5 and C6 with central lucency.



Fig. 27.5: Sagittal CT: mixed lytic and blastic appearance affecting both the anterior and posterior elements at multiple vertebral levels, most notably at C7 (CT: Computed tomography).

than the left femur (Fig. 27.2). Lumbar spine X-rays (Fig. 27.3) depicted characteristic radiographic changes of the spine with increased peripheral sclerosis and central lucency (picture frame vertebra). Plain radiographs of the cervical spine demonstrated multilevel degenerative changes with loss of the normal lordosis and a minimal anterolisthesis of C3 on C4. The C2, C3, and C4 vertebral bodies appeared sclerotic (Fig. 27.4). Computed tomography cervical spine revealed mixed lytic/sclerotic vertebra between C3 and C7 with some involvement of the

posterior elements (Figs. 27.5 and 27.6). Magnetic resonance imaging cervical spine showed severe stenosis at C3/4 secondary to degenerative disc disease and ligamentum flavum hypertrophy with resultant cord compression and myelomalacia (Figs. 27.7 and 27.8).

The patient was diagnosed with cervical myelopathy secondary to cervical stenosis with a secondary diagnosis of PDB affecting the cervical spine. He underwent an uneventful C3/4 anterior cervical discectomy and fusion with partial neurological recovery at 6 months. A histopathological

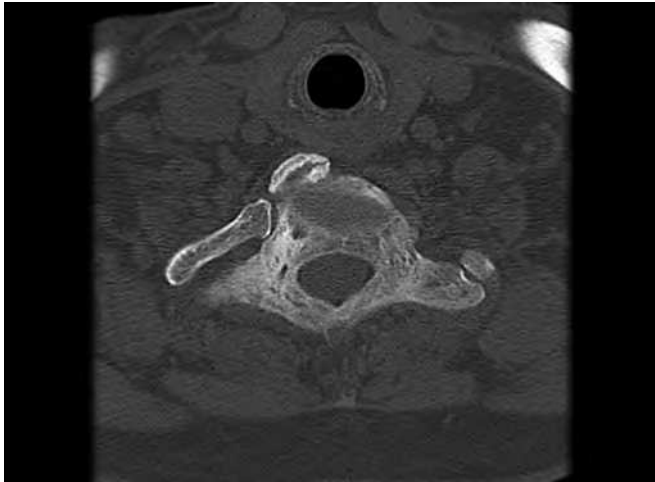


Fig. 27.6: Axial CT thru T1: coarse trabeculation with enlargement of the pedicles and posterior elements (CT: Computed tomography).



Fig. 27.7: Sagittal MRI: focal central stenosis at C3/4 with myelomalacia. (MRI: Magnetic resonance imaging).

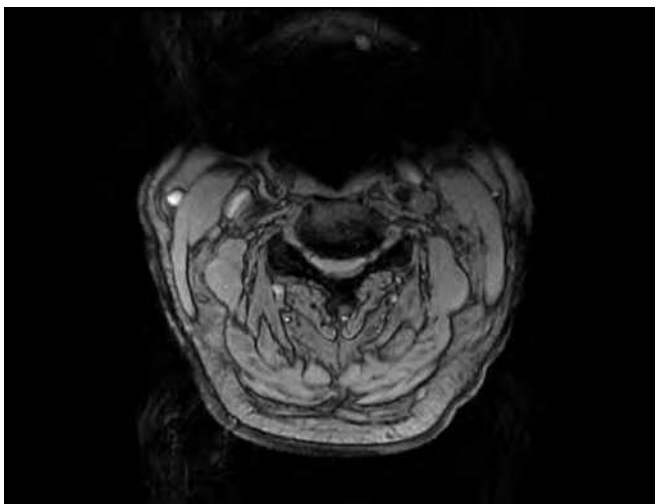


Fig. 27.8: Axial MRI at C3 level: severe central stenosis with effacement of CSF and spinal cord compression (MRI: Magnetic resonance imaging; CSF: Cerebrospinal fluid).

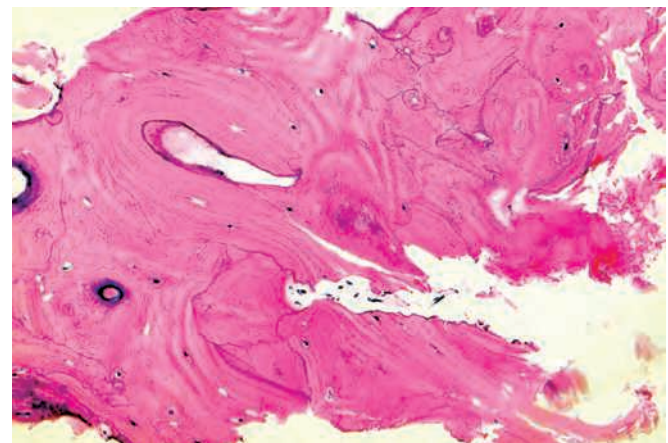


Fig. 27.9: High magnification view of a broad bone trabeculae showing disordered formation. The bone is irregular, with a mosaic pattern typical of later-stage Paget's disease highlighted by haphazard but prominent cement lines. The pattern is reminiscent of a jig-saw puzzle. Some delicate fibrosis of the marrow is also noted. *Source:* Anders KH, Anatomic and General Pathologist, Calgary Lab Services, Calgary, Canada.

specimen from surgery revealed broad trabecular bone formation that was disorganized (Fig. 27.9).

KEY POINTS

- The incidence and severity of PDB is decreasing. There is some evidence that points toward a viral etiology. A minority of cases appear to be inherited in an autosomal dominant manner.
- Pagetic bone arises from rapid osteoclastic activity with subsequent haphazard/disorganized bone formation.

- Clinical presentation may vary from asymptomatic to those having pain, deformity, fracture, or neurological compromise secondary to spinal stenosis.
- Medical management is the mainstay of treatment with spine surgery reserved for fractures and neurological dysfunction that are unresponsive to conservative measures.
- Malignant transformation occurs in <1% of all with PDB and in 2–4% of those with symptomatic PDB.

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Spinal Disorders Associated with Skeletal Dysplasias and Metabolic Diseases

Anuj Singla, Patrick J Cahill

Snapshot

- » Skeletal Dysplasias
- » Spinal Manifestations of Specific Skeletal Dysplasias
- » Metabolic and Storage Disorders

INTRODUCTION

Spinal disorders associated with skeletal dysplasias and metabolic diseases continue to remain challenging to spine surgeons in view of the relative rarity and unique natural history of these disorders. Early recognition and diagnosis are one of the most important steps in the management of these disorders and often require a multidisciplinary approach including pediatrician, spine surgeon, geneticist, and endocrinologist. Establishing the diagnosis involves a careful analysis of clinical features, family history, relevant imaging, and other diagnostic tests.

SKELETAL DYSPLASIAS

Skeletal dysplasias are systemic derangement of skeletal development involving cartilage and/or bone. Skeletal dysplasias may be classified as osteochondral dysplasias or dysostoses. Osteochondral dysplasias involve the whole skeleton while dysostoses involve only a single group of bones.¹

The initial presentation of these patients is often a screening examination in view of abnormal facial features, limb anomalies, or systemic anomalies. Screening spine radiographs coupled with a detailed physical examination often provide valuable clues to the underlying spinal disorders. Most of these spinal disorders are seen in pediatric or adolescent patients. However, adult spine

Table 28.1: Spinal disorders in common dysplasias.

<i>Dysplasia disorder</i>	<i>Spinal disorder</i>
Achondroplasia	Foramen magnum stenosis Spinal stenosis Thoracolumbar kyphosis Lumbosacral hyperlordosis
Diastrophic dysplasia	Cervical kyphosis Scoliosis Thoracic hyperkyphosis
Spondyloepiphyseal dysplasia (SED) tarda	Platyspondyly Disc herniation
SED congenita	Odontoid hypoplasia Atlantoaxial instability
Pseudoachondroplasia	Atlantoaxial instability Scoliosis

surgeons also encounter dysplastic patients with varying degrees of spinal deformities, disc herniation, or spinal stenosis. Spinal manifestations of skeletal dysplasias commonly include but are not limited to instability, deformities, stenosis, fractures, neural compression, or a combination of any of these^{2,3} (Table 28.1).

Instability of the cervical spine usually occurs at the atlantoaxial junction and less commonly at the occipitocervical junction in patients with dysplasia. Instability may occur because of bony abnormalities ranging from hypoplasia to developmental failure and/or abnormal

ossification of the cervical vertebrae, associated odontoid hypoplasia, poor ligamentous fixation of C2 resulting in C1-2 subluxation, abnormal development of the posterior processes, or ligamentous laxity.²⁻⁴ Skeletal dysplasias commonly associated with significant instability of C1-2 region include congenital SED, Kniest dysplasia, SMD, chondrodysplasia punctate, DD, and pseudoachondroplasia.^{2,3}

Periodic neurologic evaluation coupled with cervical spine radiographs should be obtained in these patients to detect early signs of instability. Flexion-extension radiographs and MRI can also be done in doubtful cases of instability.⁵

Scoliosis deformity in skeletal dysplasias is common in SED dysplasia, CDP, and DD.^{6,7} Progression of deformity in these cases may mimic the rapidly progressing congenital (dysplastic) curves or slowly progressing idiopathic type curves.^{6,7}

Sagittal plane deformities can affect any region of the spine. Thoracolumbar kyphosis is very common in achondroplasia. Lumbar spine involvement in the form of a gibbus occurs in achondroplasia.⁸ Cervical kyphosis or hyperlordosis is a very common feature of DD.⁹

Management of spinal disorders in patients with skeletal dysplasia involves careful evaluation of other skeletal anomalies, especially leg deformities, limb length inequality, and pelvic obliquity. The overall functional status of the patient with regards to ambulation and sitting balance should always be considered while formulating a treatment plan.

Surgical management of these patients is challenging to the anesthesia providers as well.¹⁰⁻¹² A detailed preoperative evaluation should always take into consideration possible difficult venous/arterial line access, difficult intubation, difficult positioning, comorbidities, abnormal chest cavity, and compromised pulmonary function.¹³ The positioning of the patient on the surgical table may require special table extension and padding equipment in view of abnormal shape and body structure.

Parents of the affected children need to be counseled in detail about the disease process and the natural history of the disorder. Evaluation of siblings to detect spinal anomalies is important as is the need for genetic counseling regarding future children.¹⁴⁻¹⁶

SPINAL MANIFESTATIONS OF SPECIFIC SKELETAL DYSPLASIAS

Achondroplasia: It is the most common nonfatal skeletal dysplasia, with an incidence of 1 in 10,000 to 1 in 30,000.^{17,18}

It is characterized by short stature (shortening of trunk with short extremities in rhizomelic pattern), frontal bossing, midface hypoplasia, normal cognitive development, and a varying degree of musculoskeletal manifestations.

Achondroplasia is caused by mutations of gene encoding fibroblast growth factor receptor-3 (FGFR3) on the short arm of chromosome 4.¹⁷ This mutation results in substitution of arginine for glycine for FGFR-3 at the physal cartilage. This mutation results in abnormal endochondral ossification of the long bones and spine, which clinically manifests as short extremities and a short trunk. It is transmitted as an autosomal dominant disorder with full penetrance. However, new mutations play a significant role in transmission, as 85% of babies with achondroplasia are born to normal parents.

The short stature is generally evident at birth or early childhood with a rhizomelic limb shortening (proximal limbs affected more than distal). Foramen magnum stenosis is usually the earliest manifestation with regard to the spine. Other spinal manifestations, which include thoracolumbar kyphosis, lumbar hyperlordosis, and spinal stenosis, may not become clinically significant until late adolescence or adulthood.

Foramen magnum stenosis: Defective endochondral bone formation at the cranial base and craniocervical junction results in a small foramen magnum, a short basicranium and clivus, a shallow posterior fossa with a horizontally oriented inferior occiput, an abnormal odontoid process, and a narrow upper cervical canal.¹ Stenosis at the foramen magnum is present in 5–10% of patients with achondroplasia, and can present with a myriad of features including those suggestive of airway compression (respiratory difficulty or apnea) or brainstem compression (apnea, lower cranial nerve involvement, hyperreflexia, paresis, or clonus). Cervicomedullary compression can be classified into severe and mild types based on the ratios of the brainstem diameter at the foramen magnum, the site of the most severe stenosis to the diameter at the pontomedullary junction, and C3 level.¹⁹

The American Academy of Pediatrics recommends screening for foramen magnum stenosis with polysomnography and computed tomography or MRI in all infants with achondroplasia.²⁰

Surgical decompression of the cervicomedullary junction is indicated in cases of severe or symptomatic cases. Bagley et al.²¹ studied the results of 46 cervicomedullary decompressions over a period of 11 years in pediatric patients with heterozygous achondroplasia and foramen magnum stenosis and reported complete resolution or



Figs. 28.1A to C: (A) Posteroanterior (PA) and (B and C) lateral radiographs of a patient with achondroplasia. The PA demonstrates narrow interpedicular distance. The lateral images demonstrate a progressive focal kyphosis deformity secondary to wedged body and short pedicle length.

partial improvement in the preoperative symptoms in all patients after surgical decompression. Cerebrospinal fluid (CSF) leak was the common complication with no other significant morbidity in their series.

Spinal stenosis: Stenosis of the spine is a very common feature of achondroplasia and can affect any region of the spine. The lumbar and cervical spines are the most common site of affliction. Stenosis is attributed to the abnormal endochondral ossification and premature fusion leading to small vertebral bodies and short (anterior to posterior) thick pedicles with narrow interpedicular distance (Fig. 28.1A). Clinically symptomatic stenosis usually occurs later in adulthood after the superimposition of degeneration. Clinical features of stenosis are present in up to 50% of adult patients.¹⁷

The indications for surgical decompression include progressive symptoms, urinary retention, significant claudication, and failure of conservative treatment.²² The surgical options include decompression by laminectomy with or without instrumentation and fusion. Carlisle et al.²³ analyzed the impact of timing of laminectomy procedures on symptom resolution in their study of 49 patients and reported a better outcome, if surgery was done early. The best results were noted, if the procedure was done within 6 months of onset of symptoms.

Laminectomy without fusion, however, has been reported to increase the chances of progression of kyphosis in immature patients.²⁴ Baca et al.²⁵ in their review of 18 immature patients with achondroplasia, reported a 3.5

times higher chance of revision surgery in uninstrumented decompressions and concluded that surgical decompression with instrumentation significantly reduces the symptoms and the likelihood of revision surgery in children.

Thoracolumbar kyphosis: Most of the children with achondroplasia have a rounded back in early infancy because of hypotonia.¹⁷ It gradually improves with age in most of the patients as they gain muscle function and tone before the true fixed kyphosis establishes itself. In a systematic review of seven studies, Engberts et al.²⁶ reported a prevalence of 50–100% thoracolumbar kyphosis in patients with achondroplasia. However, the true prevalence could not be determined because of heterogeneity of the population.

Thoracolumbar kyphosis (Fig. 28.1B) increases with hypotonia, delayed motor development, an initial measurement of $>25^\circ$, percentage of apical vertebral wedging for the height of the vertebra, and apical vertebral translation.²⁷ Persistent kyphosis has been reported to increase the risk of spinal stenosis, progression to fixed deformity,²⁸ hip flexion contracture, and lumbar hyperlordosis.²²

Pauli et al.²⁹ reported good success in preventing the development of severe kyphosis in their study of 66 kids with achondroplasia. They advocate a protocol of inhibition of unsupported sitting in early age and brace application in older children. No patient developed progressive kyphosis in their series. Siebens et al.³⁰ also reported partial correction of kyphosis in 17 pediatric patients who wore a brace. Their study also reported symptomatic relief

from back pain and neurological complaints using a brace in 31 children and adults.

Surgical correction of kyphosis is indicated in cases of kyphosis progression despite bracing, with neurological compromise (secondary to stenosis) or with kyphosis of $>50^\circ$.²² Various surgical strategies for fusion (posterior, combined anterior/posterior with anterior or posterior instrumentation, and uninstrumented fusion) have been described.^{22,31}

Ain et al.³¹ reported a series of four patients who underwent fusion using the combined anterior/posterior (two stage) instrumented fusion without any neurological complications. All patients achieved fusion in their series. Another series by Ain and Browne³² reported 100% fusion rate in patients with combined anterior/posterior (five patients) or posterior-only (seven patients) approach. Kyphosis corrected in about 50% of their patients. The complications included two cases of implant failure and one case of CSF leak.

Lumbosacral hyperlordosis: It is a very common feature of achondroplasia. It is caused by anterior pelvic tilt and the repeated squatting in case of claudicating stenosis. This leads to a protuberant belly and hip flexion contracture.²²

Femoral lengthening has been shown by Park et al.³³ to improve the hyperlordosis of the sacrum without significantly affecting the lumbar lordosis in three patients. Similar results have been reported by Vilarrubias et al.³⁴ The correction of sacral hyperlordosis is attributed to the correction of underlying pelvic femoral muscle imbalance and the resultant sacral tilt.^{33,34}

Pedicle screws are generally a safe fixation modality. However, instrumentation in these patients requires special attention in view of unique anatomical features: smaller pedicles, progressively divergent pedicles, more lateral entry points in the distal lumbar spine, and the cranial inclination of pedicles. The pedicles show a shortened anteroposterior diameter (Fig. 28.1C), and the posterior aspect of the vertebral bodies is concave. The interpedicular distances narrow progressively from the upper to the lower lumbar spine.³⁵

Diastrophic dysplasia: It is a recessively inherited skeletal dysplasia caused by irregular chondrocyte distribution at the growth plate and fibrocystic changes in the matrix. There is wide variation in the phenotype including a lethal neonatal form and the classic nonlethal forms. Rhizomelic short stature and equinovarus foot deformities are noted at birth, but sagittal or coronal spinal deformities (scoliosis, lumbar hyperlordosis, and cervical kyphosis), hitchhiker's

thumb, other deformities of the large joints, and early-onset osteoarthritis appear later.³⁶

Prenatal diagnosis for pregnancies at increased risk is possible by ultrasound examination early in pregnancy or by molecular genetic testing.^{14,37}

Cervical kyphosis: Since cervical kyphosis is already evident in some of the neonates with DD, it seems to develop prenatally. Cervical kyphosis in these patients may spontaneously resolve or progress. Remes et al.⁹ outlined the pathophysiological findings and factors associated with progression of kyphosis: angle $>60^\circ$, severe hypoplasia in C3–C4, wedge-shaped vertebral body, pathological loading of cartilaginous parts in the vertebrae, and extensor-flexor muscle imbalance. They reported the natural history of cervical kyphosis in 120 patients with DD. Of these 120 patients, 29 (24%) were noted to have kyphosis; in 25 patients, the first radiographs were taken before the age of 18 months, and 24 (96%) had cervical kyphosis. Most of the kyphosis in their series resolved spontaneously by 7 years of age. However, they noted severe, rapid progression of deformity in cases that did not resolve. The deformities need to be followed closely, as these progress very rapidly and can prove fatal.⁹

The indications for surgical stabilization and decompression include severe, progressive deformity, and neurological symptoms. Combined anterior/posterior fusion is reported to be better in these patients.⁹

Scoliosis: It is a common feature in patients with DD, with an incidence of 37–88%.^{6,38} Most of the deformities do not progress significantly; however, patients who present very early in childhood with severe deformities tend to progress rapidly.⁶ Remes et al.⁶ reported an incidence of scoliosis in 88% of cases (86 out of 98 patients) in a major series of patients with DD. They also proposed a classification for scoliosis in DD based on progression: early progressive, idiopathic-like, and mild nonprogressive. The early progressive type resembles infantile progressive idiopathic scoliosis with regard to early onset, rapid progression, and severe deformity manifestation. Mild, nonprogressive types can be easily distinguished and followed. Idiopathic types behave similar to idiopathic juvenile or adolescent curves and can be treated as per the individual curve progression. This classification system is proposed as a good tool for predicting natural history of scoliosis in DD and for adjusting the timing of surgery in individual patients.

Early progressive curves require early fusion, as these curves tend to progress very rapidly. Both combined anterior/posterior and posterior-only fusion have been

suggested.³⁹ Matsuyama et al.³⁹ reported the outcome of surgical arthrodesis for scoliosis in 21 patients with DD. Four were managed with posterior-only fusion; pseudarthrosis requiring revision surgery developed in two out of these four patients. Combined anterior and posterior procedures achieved better fusion.

Thoracic kyphosis: Thoracic hyperkyphosis is a very common feature of DD and is associated with scoliosis. The apex of the kyphosis is usually at the junction of the thoracic and lumbar scoliosis curves. The kyphosis is reported to progress very rapidly and necessitates early intervention to prevent catastrophic deformity.³⁹

In the same series, Matsuyama et al.³⁹ reported 15 cases of hyperkyphosis in 21 patients with DD. The average correction was 21° (0°–62°), with fusion achieved in 15 patients. The kyphosis correction was preserved at follow-up. The aim of the surgery was to prevent the progression of the curves as opposed to actually achieving deformity correction.³⁹

Spondyloepiphyseal dysplasia: It is characterized by abnormal growth of the spinal vertebrae and epiphysis leading to short-trunk dwarfism with shortened proximal and middle limbs and relative sparing of hands and feet.¹ There are two different types of SED: SED tarda and SED congenita.

I. **Spondyloepiphyseal dysplasia tarda:** It is an X-linked recessive disorder caused by abnormal type II collagen. It is characterized by short stature resulting from platyspondyly (humping and eburnation of the central and posterior part of the end plates) and progressive arthropathy. The epiphyses in the long bones are dysplastic, especially in the proximal parts of the limbs. Precocious arthritis develops in the hips as well as in the spine.⁴⁰

This disorder may cause a predisposition to multiple thoracic disc herniation,⁴¹ which may rarely lead to spastic paraplegia.⁴² No other significant symptomatic affliction of the spine has been reported with this disorder.

II. **Spondyloepiphyseal dysplasia congenita:** It is an autosomal dominant disorder. It is the more severe form of the disorder and is commonly associated with serious spinal abnormalities in children. The prominent recognizable feature present at birth is cleft palate. Also, eye involvement is common in the form of high-grade myopia and retinal detachment. The other common features include short neck, pectus carinatum, and barrel-shaped chest.

The vertebral bodies are irregular and flat with narrow disc spaces, small sagittal atlas diameter, odontoid hypoplasia, loose or lax ligaments, and atlantoaxial subluxation.

Atlantoaxial instability associated with odontoid hypoplasia or ligamentous laxity is the most common spinal manifestation of SED congenita in children. Myelopathy can present clinically in various degrees of neural deficit including paralysis and potentially serious respiratory complications. Instability has been reported to progress with age and increasing atlantodental interval (ADI).^{1,43} Most of the patients with myelopathy have been reported to have an ADI >5 mm.⁴⁴ Sagittal canal diameter of <10 mm at the level of the atlas is associated with severe cord compression.^{43,44} Stabilization of the atlantoaxial region with or without decompression is indicated in symptomatic patients with severely stenotic deformity.¹ Miyoshi et al.⁴³ reported the surgical outcome of reduction and stabilization in seven out of 29 patients with SED of which six underwent surgery for myelopathy. C1 laminectomy was required in all of their cases to achieve satisfactory reduction. Ain et al.⁴⁵ reported a successful fusion in six out of seven patients with SED with no other significant complications. Four of their patients with neurological symptoms improved after fusion.

Pseudoachondroplasia: It is a form of short limb dwarfism characterized by involvement of both epiphyses and metaphysis. Skeletal manifestations involve marked joint laxity and instability leading to severe premature osteoarthritis. Two autosomal dominant (mild) and two recessive (more severe) variants of pseudoachondroplasia have been described.

The long bones show marked flaring and irregularity of metaphyses with delayed maturation of epiphyses, which are small and irregular. Maturation is significantly delayed in the triradiate cartilage and entire acetabulum.⁴⁶ Spine radiographs show anterior beaking of vertebrae and/or platyspondyly. Odontoid hypoplasia, a very common feature, leads to upper cervical spine instability that increases with the age.

Shetty et al.⁴⁷ studied the upper cervical spine in 15 patients with pseudoachondroplasia. Os odontoidum (incomplete fusion of the os odontoid process to the body of the axis) was present in 60% of their patients. Radiological evidence of os odontoidum and atlantoaxial instability did not warrant surgery in their study, as no signs of cervical myelopathy developed or progressed in their patients during the follow-up period. However, this study emphasized the need for regular clinical and radiological

evaluation to detect early signs of neurological involvement. Ain et al.⁴⁵ reported successful fusion for upper cervical instability in five patients with pseudoachondroplasia. One of their patients developed instability below the fused segment with a worsening of neurologic status.

Mild thoracic or thoracolumbar scoliosis is common in these patients, as is mild spinal stenosis.

Kniest syndrome: It is a disorder of type II collagen characterized by short stature as well as severe ophthalmic involvement including retinal detachment, cataracts, and visual loss. Musculoskeletal features include short limbs with enlarged and stiff peripheral joints. Radiographic features include platyspondyly, hypoplastic femoral head, and enlarged epiphysis of long bones with cloud-like calcification.⁴⁸

Atlantoaxial instability similar to other common dysplastic syndromes has been reported⁴⁹ and requires periodic clinical and radiographic evaluation. Stabilization is indicated in cases of neurological involvement or severe instability. Ain et al.⁴⁵ in their series of 25 patients with skeletal dysplasias, reported two patients with Kniest syndrome who underwent successful atlanto-occipital fusion. Spine deformities do not progress much, because the trunk is stiff. Scoliosis is generally mild and does not usually require treatment.

Metatropic dysplasia (MD): It is a rare skeletal dysplasia caused by a mutation in the *VDRL4* gene leading to abnormal endochondral ossification. The phenotypic variability of MD has led to a classification based on radiological anomalies dividing into three different types: a lethal autosomal recessive form, an autosomal recessive nonlethal form, and a nonlethal autosomal dominant form with less severe radiographic manifestations and a better clinical outcome.

Characteristic abnormalities include tubular bones with short diaphyses and wide metaphyses (dumbbell-like configuration) of long bones, delayed ossification of the ischiopubic bone, platyspondyly, precocious calcification of hyoid and cricoid cartilage, and irregular and squared-off calcaneal bones.⁵⁰

The main spinal manifestation is progressive kyphoscoliosis, which develops early and usually requires surgical intervention by preadolescence. The scoliosis tends to progress and becomes rigid in untreated patients.⁵¹ Another spinal manifestation is compression of the cervical spinal cord by foramen magnum stenosis and atlantoaxial instability. Spinal fusion with or without decompression is indicated for radiologically proven atlantoaxial instability.⁵²

Thanatophoric dysplasia: It is an uncommon dysplasia characterized by significant involvement of the base of the skull, spine, ribs, and appendicular long bones. Malformations of the vertebral laminae, most prominent in the basiocciput and atlas vertebra, lead to compression of the cervical spinal cord. Stenosis of the foramen magnum and spinal canal may contribute to the ventilatory insufficiency that often causes death in these patients.⁵³

Chondrodysplasia punctata: It is a rare skeletal dysplasia characterized by stippled epiphyses during infancy. It is caused by arylsulfatase (ARS) E deficiency. Although the symptoms are usually mild, severe spinal cord compression by dysplastic vertebrae may develop.

Mason et al.⁷ identified three patterns of spinal involvement in their series of 20 patients: cervical bony disruption; a slowly progressive, nondysplastic scoliosis responding well to standard fusion techniques; and a dysplastic kyphoscoliosis, which is rapidly progressive and resistant to fusion. Dysplastic scoliosis may require multiple surgical procedures. The best results in dysplastic curves are reported with an anterior strut graft and a posterior fusion.⁷

Campomelic dysplasia: It is a rare autosomal dominant skeletal dysplasia classically characterized by bent bones of the extremities, tracheobronchial narrowing, thoracic kyphoscoliosis (Figs. 28.2A to D), and various degrees of phenotypic sex reversal. Incomplete ossification of the cervical vertebral pedicles results in congenital cervical instability and kyphosis.⁵⁴ The late ossification of the midthoracic pedicles is a characteristic radiologic feature.

Coscia et al.⁵⁵ advocated aggressive treatment of spinal deformities in their series of eight patients. Vertebral body hypoplasia is reported to be the cause of deformities that include scoliosis, thoracic hyperkyphosis, and cervical kyphosis.

Spondylometaphyseal dysplasia: It is a group of skeletal dysplasias that principally involve the spine and the metaphyses of long bones. It is characterized by short stature, developmental coxa vara, fragmented appearance of the metaphysis (corner fractures), abnormally shaped vertebrae, and odontoid hypoplasia.⁵⁶ Spinal deformities, including scoliosis, kyphosis, and cervicomedullary instability, have been reported in this rare dysplastic disorder.

Spondyloepimetaphyseal dysplasia: It is a rare skeletal dysplasia frequently associated with severe spinal deformity. The orthopedic manifestations can include hypoplastic odontoid with atlantoaxial instability, severe kyphosis or lordosis of the dorsal and lumbar spine, hip subluxation,



Figs. 28.2A to D: Spine radiographs of a patient with campomelic dysplasia showing severe early onset kyphoscoliosis (A and B) before and (C and D) after application of VEPTR (vertical expandable prosthetic titanium rib) device.

Table 28.2: Common spinal involvement in mucopolysaccharidosis (MPS).

<i>MPS</i>	<i>Enzyme deficiency</i>	<i>Spinal disorder</i>
MPS IVA (Morquio syndrome)	N-acetyl-galactosamine-6-sulfate sulfatase	Odontoid hypoplasia Atlantoaxial instability Spinal canal stenosis Cord compression Thoracolumbar kyphosis
MPS I (Hurler syndrome)	α -L-iduronidase	Odontoid hypoplasia Atlantoaxial instability Thoracolumbar kyphosis/scoliosis
MPS II (Hunter syndrome)	Iduronate-2-sulfatase	Cervical myelopathy Atlantoaxial instability Gibbus
MPS VI (Maroteaux-Lamy syndrome)	Arylsulfatase B	Thoracolumbar gibbus

coxa vara, genu valgum, club foot, and early severe hip osteoarthritis.⁵⁷ These deformities, which can appear early in life, progress rapidly and are potentially fatal.

METABOLIC AND STORAGE DISORDERS

Mucopolysaccharidoses and mucolipidoses are inborn storage diseases, caused by deficiency of lysosomal degradation enzyme. Musculoskeletal manifestations are attributable to intracellular accumulation of undegraded substrates within the lysosomes of chondrocytes, the extracellular matrix of articular cartilage, and synovium⁵⁸ (Table 28.2). Most of these disorders are transmitted in an autosomal recessive pattern with the exception Hunter's syndrome, which is X-linked recessive.⁵⁹

Most children with MPS are born with very few distinguishing features, including coarsened facial features such as fullness of the skin, full eyebrows, enlarged tongue, retained epicanthal folds, and short neck and do not manifest any significant growth or development issues in the 1st year or more of life.⁵⁸

Cervical spine involvement in the form of atlantoaxial instability and odontoid hypoplasia is a common feature of lysosomal storage disorders like Morquio, Maroteaux-Lamy, and Hurler syndromes.⁶⁰ Atlantoaxial instability and odontoid hypoplasia can lead to severe neurological impairment and death. Spinal stenosis is the result of a complex interplay of glycosaminoglycan (GAG) accumulation behind the odontoid process, dural thickening, and C1 ring hypoplasia. The accumulation of soft tissue results in progressive stenosis and compression of the spinal cord

at the occipitocervical junction. Significant instability (>8 mm) and cord signal change on MRI are indications for surgical stabilization.⁵⁸

Acute thoracolumbar kyphosis is a classic gibbus deformity and a common radiographic finding in patients with MPS. Levin et al.⁸ studied the lumbar gibbus in storage disorders and reported that all patients had localized gibbus of the upper lumbar spine, characterized by anterior wedging and posterior displacement of the vertebrae at the apex of the curve, producing a beaked appearance. The curve is generally at or below the conus and is most severe in patients with MPS-IV. Neurologic complications are unusual in these patients. Continued progression $>70^\circ$ or myelopathy are indications for fusion, which is generally combined anterior and posterior in most of these patients.⁵⁸

Some of the more common storage disorders that affect the spine are briefly described here.

Morquio syndrome (MPS IVA): It is a lysosomal storage disorder caused by a deficiency of the enzyme N-acetylgalactosamine-6-sulfate sulfatase, causing progressive accumulation of keratan sulfate (KS) and chondroitin 6 sulfate (C6S) in tissues. Because KS and C6S are major components of proteoglycans in cartilage and bone, MPS IVA mainly manifests as skeletal dysplasia and short stature. Mucopolysaccharidosis IVA is multisystemic but manifests primarily as a progressive skeletal dysplasia, especially involving the spine.^{58,61}

Significant phenotypic variations can vary from very mild to severe. The onset of symptoms typically occurs prior to 1 year of age in rapidly progressing patients and generally in the second decade of life in slowly progressing patients. Severe phenotype may be associated with death in the second or third decade caused by paralysis from cervical myelopathy, respiratory insufficiency, and heart abnormalities.

Spinal involvement in MPS IVA occurs at two distinct sites. Cervical spinal involvement, particularly instability and compression at the C1–C2 level, is a near universal finding and predisposes patients to myelopathy, paralysis, and sudden death.⁶² Spinal cord compression due to kyphotic deformity at the thoracolumbar level is not as common but can lead to paraplegia with insidious onset.

Cervical spine subluxation and instability: Cervical spinal involvement, particularly instability and compression at the C1–C2 level, is thought to arise from a combination of dens hypoplasia and ligamentous laxity. Cervical instability is pathologic in MPS when the ADI is >5 mm at any age or there is a difference of >2 mm in ADI on flexion–extension lateral radiographs.⁶¹

Solanki et al.,⁶³ in their MRI evaluation of the spine in MPS-IV, suggested that the spine is narrower at C1–2, appearing as an inverted funnel shape. The sagittal diameter and axial surface area of both the spinal canal and cord are reduced.⁶³

Indications for surgery include the development of pathologic reflexes and neurological deficits with instability on neurological examination. Foramen magnum decompression is indicated in cases of associated compression at the foramen magnum. Posterior occipitocervical fixation and fusion with instrumentation and bone graft is the most recommended approach.^{49,63} Ain et al.⁴⁵ analyzed the outcome of occipitocervical fusion in seven patients with MPS IV, all of whom underwent successful fusion. Five of these seven patients had neurological symptoms secondary to instability, and in all except one patient the neurological symptoms resolved after fusion.

Spinal canal stenosis and cord compression: Generalized thickening of the posterior longitudinal ligament and the ligamentum flavum due to GAG deposition is the prime etiological factor for spinal stenosis. The stenosis along with cervical instability, cartilaginous and ligamentous hypertrophy at the atlantoaxial joint, disc protrusion, and thoracolumbar kyphosis can cause diffuse cord compression.⁶¹

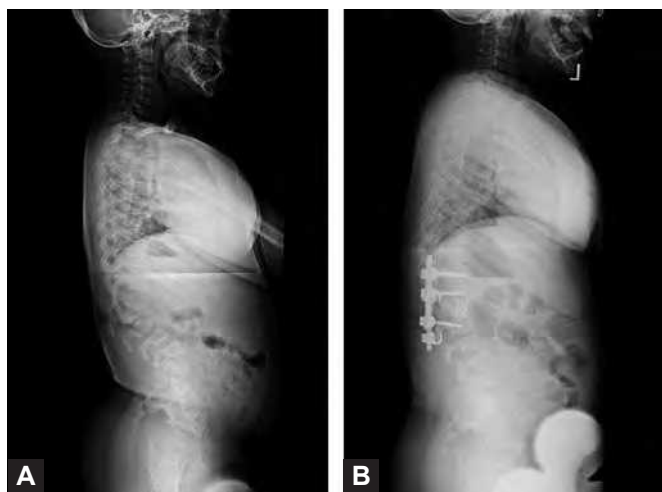
Evidence of cord compression with signal change on MRI even without symptoms is an indication for decompression and stabilization surgery. Combined anteroposterior fusion in association with anterior discectomy is highly recommended.

Regular neurological and radiological monitoring is strongly recommended to ensure early detection of instability or cord compression.

Typical problems with anesthesia in MPS-1 include airway obstruction, intubation difficulties or failure, possible emergency tracheostomy, and cardiovascular and cervical spine issues.⁶⁴

Mucopolysaccharidosis type I (MPS I) (Hurler syndrome): It is a chronic, progressive, multisystemic lysosomal disease caused by a deficiency of α -L-iduronidase enzyme. Mucopolysaccharidosis I is commonly classified into three clinical syndromes: Hurler, Hurler-Scheie, and Scheie. Hurler syndrome is the most severe phenotypic form and is described below.

The most common manifestations of MPS I include a characteristic facies, corneal clouding, macroglossia, hearing loss, hydrocephaly, cardiopathy, respiratory problems, hepatosplenomegaly, inguinal and umbilical hernia, dysostosis multiplex, limited joint mobility, and cognitive



Figs. 28.3A and B: Hurler's syndrome. (A) Prominent thoracolumbar kyphosis secondary to the wedged vertebral body. (B) Post-operative images after surgical correction via a posterior-based vertebra resection and stabilization with an anterior cage and posterior screws and hook construct.

impairment. The symptoms arise after birth and progress rapidly. Untreated patients have a very high mortality rate in the first decade of life due to complications related to brain damage or cardiorespiratory problems.⁶⁵

- **Spinal involvement:** Accumulation of GAGs in paraspinal ligaments increases the potential for morbidity, resulting in major risks to the cervical column. Odontoid hypoplasia is a common feature in these patients and predisposes to instability and subluxation at the cervicomedullary region. Deformities in the form of thoracic kyphosis⁶⁶ (Figs. 28.3A and B) and thoracic/lumbar scoliosis are also common.

Tandon et al.⁶⁷ described the spinal problems in 12 patients with this disorder. Kyphosis in proximal lumbar region was the most common spinal affection in their study. The other spinal manifestations included odontoid hypoplasia and thoracic scoliosis. Neurological problems were reported in two of their patients.

In a review of MPS I, van der Linden et al.⁶⁶ reported musculoskeletal problems in 399 patients. The most frequent musculoskeletal abnormalities reported in their study included odontoid hypoplasia (72%), thoracolumbar kyphosis (81%), genu valgum (70%), hip dysplasia (90%), and carpal tunnel syndrome (63%).

Bone marrow transplantation has increased the survival of these patients, but musculoskeletal manifestations seem largely unresponsive to hematopoietic stem cell transplantation.^{66,68}

Mucopolysaccharidosis type II (MSP II) (Hunter syndrome): It is a rare genetic disease caused by deficiency of the lysosomal enzyme iduronate-2-sulfatase. Mucopolysaccharidosis II is the only MPS with X-linked inheritance. Common causes of death, which usually occurs within the second decade of life, are obstructive airway disease and cardiac failure due to valvular dysfunction, pulmonary hypertension, and myocardial disease.

Accumulated GAGs in joints and connective tissue lead to significant skeletal deformities including spastic paresis due to cord compression at the craniocervical region, vertebral and rib abnormalities, pelvic dysplasia, severe hip disease, and joint contractures.

Spinal cord compression/cervical myelopathy: GAG accumulation in the spinal meninges leads to spinal cord compression. Clinically, patients may present with quadriplegia and/or spasticity. Gibbus deformity and/or atlantoaxial subluxation may aggravate spinal canal stenosis.

Other neurological complaints suggestive of spinal cord compression include urinary retention secondary to neurogenic bladder. Surgical decompression in MPS II is required, and in order to achieve a satisfying outcome, it may be crucial to perform surgery at an early stage of the disease.⁶⁹

Mucopolysaccharidosis type VI (Maroteaux-Lamy syndrome): It is a rare autosomal recessive genetic disease caused by deficiency of the enzyme *N*-acetylgalactosamine-4-sulfatase or ARSB.

Patients with MPS VI exhibit a chronic and progressive course, where primarily the skeletal and cardiopulmonary systems, cornea, skin, liver, spleen, brain, and meninges are affected. In general, patients have a short trunk and a thoracolumbar gibbus.

Most of the individuals with MPS VI progress to death in their second or third decade of life as a result of heart failure.

Mucopolipidosis: I-cell (mucopolipidosis 2) is a rare, autosomal recessive neurodegenerative lysosomal storage disease. Neonatal skeletal radiographs have features resembling hyperparathyroidism and rickets, and are present during the 1st year of life. Prominent radiographic findings include a butterfly vertebral body and irregular epiphyseal ossification.⁷⁰

SUMMARY

Spinal disorders associated with dysplasias and metabolic disorders continue to remain challenging despite recent advances in diagnostic imaging and spinal instrumentation systems. The principle of treatment in these disorders remains the same: early recognition and stabilization of

neurologically unstable or potentially fatal unstable segments, preventing significant progression of deformities, and ensuring a good quality of life. These patients often need multidisciplinary care in view of the systemic involvement and comorbidities.

KEY POINTS

- Early recognition and diagnosis are one of the most important steps in the management of skeletal dysplasias and associated spinal disorders.
- Periodic neurologic evaluation along with cervical spine radiographs should be done in most patients with skeletal dysplasias to detect early signs of atlantoaxial instability. Flexion-extension radiographs and magnetic resonance imaging (MRI) can also be done in uncertain cases of instability. Common dysplasias associated with instability include congenital spondyloepiphyseal dysplasia (SED), Kniest dysplasia, spondylometaphyseal dysplasia (SMD), chondrodysplasia punctata (CDP), diastrophic dysplasia (DD), and pseudoachondroplasia.
- Achondroplasia is the most common nonfatal skeletal dysplasia. Foramen magnum stenosis is usually the earliest manifestation with regards to the spine. Other spinal manifestations include thoracolumbar kyphosis, lumbar hyperlordosis, and spinal stenosis associated with shortened pedicles. Stenosis may present in late adolescence or adulthood.
- Atlantoaxial instability is the most common spinal manifestation in SED congenita. Myelopathy can cause neural deficits including paralysis and potentially serious respiratory complications. Stabilization of the atlantoaxial region with or without decompression is indicated in symptomatic patients with severe stenosis.
- The upper cervical spine is involved in mucopolysaccharidosis (MPS) IV, MPS I, and MPS VI. Significant instability and cord signal change on MRI are indications for surgical stabilization.

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Operative and Nonoperative Management of Rheumatoid Arthritis

Jeremey Reynolds, Christopher Brown

Snapshot

» Diagnostic Challenges

INTRODUCTION

Incidence

Rheumatoid arthritis is a chronic inflammatory condition of unknown etiology predominantly affecting synovial joints, but with the potential for numerous systemic manifestations. It is more common in women¹ and in middle age.² One study suggested that the lifetime risk of developing rheumatoid arthritis may be as high as 3.6% of women and 1.7% of men in the United States.¹ The spine is commonly affected; the cervical spine being involved in ~40% of patients.³ These patients are at risk of cervical myelopathy, progressive neurological damage, and death.⁴ Interestingly, while hospitalization for other severe manifestations of rheumatoid arthritis has decreased significantly in recent years, this does not appear to be true for rheumatoid cervical myelopathy.⁵

Pathology

Inflammation in rheumatoid arthritis has a predilection for synovial joints. The typical presentation is with a symmetrical arthritis affecting the small joints of the hands and the feet. Histologically, there is a thickened synovium with increased vascularity and cellularity, in particular T cells, macrophages, and plasma cells. Joint destruction, instability, and deformity are thought to result from the formation of an inflammatory pannus that adheres to the articular cartilage and produces proteinases, destroying first cartilage and then bone.⁶

Spinal Manifestations

At its most severe, erosion of bone and ligamentous structures in the spine can lead to instability and devastating neurological consequences. The most common manifestation of rheumatoid spinal disease is anterior atlantoaxial subluxation, occurring in ~14% to 23% of patients.^{7,8} Movement at the atlantoaxial joint can also occur less commonly posteriorly, vertically, and laterally. Subaxial subluxation occurs in 5–19% of patients,^{7,8} and subcervical disease can also occur. Predictors of cervical spine disease include severe erosive peripheral joint disease⁸ and use of corticosteroids.⁹ Symptoms include headache, neck pain, and symptoms of spinal cord compression, which always demands urgent investigation. However, according to Neva et al., only 69% of those with radiographic evidence of subluxation reported neck pain.³ Importantly, once objective evidence of neurological impairment has developed, progression appears virtually inevitable and chances of recovery following surgery are reduced.¹⁰

Medical Management of Rheumatoid Arthritis

Essential to the successful management of rheumatoid arthritis is a multidisciplinary approach, involving both early disease-modifying pharmacological treatment to reduce joint deformity and disability, but also pain management and functional restoration strategies.

Pain Management

Despite the advent of disease-modifying antirheumatoid drugs (DMARDs), the majority of rheumatoid arthritis patients continue to experience pain¹¹ and rank pain as one of the most important areas in which they would like to see improvements.¹² Unfortunately, many studies into pain management of rheumatoid arthritis are of varying quality and were carried out in the pre-DMARD era. Multinational recommendations support the use of paracetamol as a first choice analgesic, with consideration of adding a drug of a different class if this is ineffective.¹³ Renal, cardiovascular, and other comorbidities must be taken into consideration, though no studies have directly addressed these groups.¹⁴ Despite a lack of convincing supporting evidence, tricyclic antidepressants or neuromodulators may be a helpful addition in some patients, but muscle relaxants or systemic glucocorticoids are not recommended for pain relief.¹³ Nonpharmacological strategies such as hydrotherapy and orthotics can also reduce pain and maintain function.

Rehabilitation and Functional Restoration/Preservation

Despite modern disease-modifying treatment, many rheumatoid arthritis patients still report reduced function and ability to work.^{15,16} Patients with atlantoaxial involvement have reduced range of motion and neck strength compared to other rheumatoid arthritis patients.¹⁷ No studies have specifically assessed rehabilitation in rheumatoid arthritis patients with spinal involvement. However, general strategies that may be of benefit include resistance and aerobic exercise,^{18,19} hydrotherapy,²⁰ occupational therapy,^{21,22} and splints.^{23,24} Neck exercises should be avoided in patients with unstable atlantoaxial subluxation as it may decrease the width of the spinal canal.²⁵

Evolution of DMARDs

Disease-modifying antirheumatoid drugs are agents that slow disease progression and have shown good efficacy at reducing peripheral joint inflammation. They can be either synthetic, such as methotrexate, or biological agents. It has become recognized that early DMARD treatment²⁶ and tight control of inflammation²⁷ are needed to reduce long-term deformity and disability. Due to a combination of evidence of effect^{28,29} and a relatively acceptable (compared to other DMARDs) safety profile, methotrexate represents

the most commonly used first-line agent. For those unable to tolerate methotrexate, or where it is contraindicated, options include other nonbiological DMARDs such as sulfasalazine or leflunomide. If active inflammation continues despite synthetic DMARD therapy, consideration can be given to a biological agent, most commonly a tumor necrosis factor (TNF) inhibitor, usually in combination with methotrexate.^{30,31} Other second-line agents with effects on skeletal manifestations include the B-cell depleting medication, rituximab³² and the anti-interleukin 6 agent, tocilizumab.³³

The effects of DMARDs on spinal and systemic manifestations have been less well studied and further evidence is needed. While combination DMARD therapy may not show overall benefit over methotrexate alone in peripheral joint inflammation,³⁴ there is limited evidence that it may reduce atlantoaxial subluxation.³⁵ A noncontrolled retrospective cohort study also suggested that biological treatments may reduce the development of new cervical spine lesions, but not pre-existing lesions.³⁶ While a wide variety of disease-modifying and immunosuppressive medications have been tried for systemic manifestations, the evidence is limited and mainly restricted to case reports and small studies.

Imaging

In cases of known rheumatoid arthritis, imaging is required to detect and monitor (1) spinal instability and alignment, and (2) neurological compression and on occasion radiological changes within the spinal cord before clinical manifestations occur. In addition, a detailed knowledge of the individual's bony anatomy may be required to plan the placement of surgical implants.

Dynamic plain radiographs (taken with the head in flexed and extended positions) are used as well as the standard anteroposterior, lateral, and odontoid peg views (Fig. 29.1). These can be used to aid the identification of instability although the definition of instability itself is widely debated. Collins et al. reported that 50% of patients with abnormal cervical spine X-rays were asymptomatic.³⁷ Computed tomography (CT) provides useful assessment of bony anatomy, and software reconstructions of the axial sequences can provide three-dimensional imaging. However, magnetic resonance imaging (MRI) gives the most comprehensive view of soft-tissue and bony spinal involvement in rheumatoid arthritis. Cross-sectional imaging with

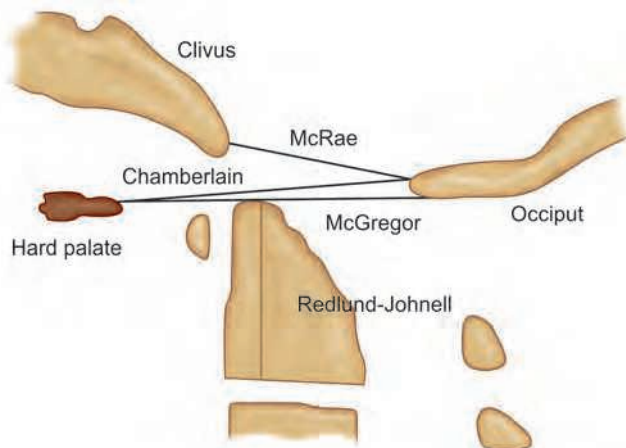


Fig. 29.1: Radiographic measurements of OC and C1-2 instability.

both these modalities eliminates overprojection from adjacent structures. Increased signal on MRI T2-weighted sequences can identify changes due to spinal cord compression in addition to detailing the cord contour and identify the pathology (e.g. pannus, C) occupying the perineural space. In common with other spinal pathologies such as standing position and flexion-extension, MRI will probably become more widely used to provide more “real-time” information and allow better correlation with symptoms.

DIAGNOSTIC CHALLENGES

Failing Musculoskeletal System versus Progressive Neurological Deficit

Muscle weakness is a common symptom in rheumatoid arthritis and can have a variety of causes. A key challenge can be differentiating between weakness due to joint inflammation, myopathy, peripheral neuropathy, and spinal cord compression. Clinically, it can be helpful to consider the pattern of distribution of the weakness. Whereas joint pain resulting in muscle disuse would be expected to be local to the affected joint with no increase in tone, spinal cord compression would typically result in a distinct sensory level, with spastic muscle weakness, and possibly bladder and bowel disturbance. Myopathic weakness, due to inflammation or medications, would be expected to be predominantly proximal and symmetrical, whereas peripheral neuropathy would typically be distal, or affect specific peripheral nerves as part of mononeuritis multiplex.

Grading Myelopathy

Grading systems permit a reproducible means of measuring disease progression and the influence of intervention. Grading of neurological deficit in rheumatoid arthritis is complex as spinal cord abnormalities, peripheral nerve compression, and joint arthropathy all lead to symptoms and signs that underlie disability. Functional capacity is most usually graded using the Ranawat scale:³⁸

- No neurological deficit
- Subjective weakness, dysesthesia, and hyper-reflexia
- Objective weakness and long-tract (upper motor neuron) signs; patient is still ambulatory
- As above but patient is no longer ambulatory

Disease-specific Local Challenges

It is important to recognize that rheumatoid arthritis is not simply a disease of joint inflammation, but can have a variety of other local and systemic effects which may be relevant when planning surgery.

Osteopenia/Osteoporosis

Decreased bone mineral density in rheumatoid arthritis is common³⁹ due to a combination of immobility,⁴⁰ inflammation,^{39,41} glucocorticoid treatment,^{39,41} and the female preponderance of rheumatoid arthritis.¹ It can be local, systemic, or periarticular, resulting in increased fracture risk and challenging spinal surgery. Greater disease activity and longer duration of disease appear to be particularly important determinants of bone loss in rheumatoid arthritis,^{39,41} suggesting an important role of inflammation. However, while anti-TNF treatments may halt decreases in bone mineral density,^{42,43} the effects of methotrexate and other nonbiological DMARDs are less clear.⁴⁴ To help identify those at greatest risk, one study demonstrated that a combination of five criteria (age, weight, immobility, inflammation, and ever having used glucocorticoids) had a sensitivity of 82% and specificity of 45% for identifying osteoporosis on dual energy X-ray absorptiometry scanning.⁴⁰

Temporomandibular Joint Dysfunction

Approximately half of rheumatoid arthritis patients have symptoms or signs of temporomandibular (TMJ) joint dysfunction,⁴⁵ such as TMJ pain, clicks or crepitus, and less commonly, restriction of mouth opening. Obstructive

sleep apnea due to rheumatoid arthritis-induced retrognathia has also been reported.^{46,47} If cervical spine surgery is being considered, the effect of coincident TMJ disease must also be taken into consideration as spinal fixation in an inappropriate position may affect an already limited mouth opening. This is potentially important as in one study, half of those with severe cervical spine arthritis on imaging also had a severe TMJ disease.⁴⁸

Esophageal Dysmotility

Investigations into esophageal dysmotility in rheumatoid arthritis are largely confined to small case-control studies and case reports. However, the evidence that is available suggests that approximately one-third or more of rheumatoid arthritis patients may demonstrate dysphagia and more may show asymptomatic esophageal motor abnormalities.⁴⁹⁻⁵¹ Consideration should therefore be given to the effects of this when planning surgery on the cervical spine. Causes may include vasculitis, amyloidosis, cricoarytenoid dysfunction, and xerostomia. There is also a single case report of acute dysphagia secondary to a rheumatoid pannus involving the anterior cervical spine and causing esophageal compression.⁵²

Risk of Deep Vein Thrombosis

Rheumatoid arthritis is associated with an approximately twofold increased risk of deep vein thrombosis (DVT) and pulmonary embolism^{53,54} among both hospitalized patients and outpatients. Surgery and ensuing immobility may increase this further. Although some studies had suggested that anti-TNF medications may increase DVT risk further still,^{55,56} this is not borne out compared to nonbiological DMARDs in a large registry study.⁵⁷

Myocardial Infarction

Rheumatoid arthritis is associated with increased premature mortality,⁵⁸ largely due to an ~50% increased risk of cardiovascular disease.⁵⁹ Myocardial infarction in rheumatoid arthritis patients also appears more likely to go unrecognised⁶⁰ and be recurrent than in the general population.⁶¹ For this reason, risk of cardiovascular disease must be considered in all rheumatoid arthritis patients, especially preoperatively. Potential explanations include systemic inflammation-induced endothelial dysfunction⁶²; similarities exist between the pathological processes underlying rheumatoid arthritis and atherosclerosis⁶³

and an excess of traditional cardiovascular risk factors in rheumatoid arthritis patients. Supporting the role of inflammation in the increased cardiovascular disease risk, patients on methotrexate and those who show a positive response to anti-TNF therapies have a reduction in cardiovascular events.⁶⁴

Immunosuppression

Rheumatoid arthritis patients have an inherent increased risk of certain infections^{65,66} and malignancies such as lymphoma⁶⁷ than the general population. This may be further confounded by the use of anti-TNF therapies,^{66,68} methotrexate and glucocorticoids as treatments,⁶⁹ especially during the first 6 months of anti-TNF treatment. Whether the risk of immunosuppression is such that DMARDs should be stopped preoperatively to reduce postoperative infections is a controversial area. While spinal surgery was not specifically studied, methotrexate does not appear to need to be stopped in patients undergoing elective orthopedic surgery.⁷⁰ The situation for anti-TNF therapies has not been well investigated;⁷¹ however, various national guidelines recommend consideration that they be stopped.

Regional Spinal Disease

Atlantoaxial subluxation (AAS) is defined as a preodontoid interval >3 mm that is not static in dynamic lateral films.⁷² Anterior is the most common direction for this to occur, and lateral subluxation is usually seen in conjunction with rotational deformity.⁷³ The space available for the spinal cord decreases as the preodontoid interval (or anterior atlantodental interval, AADI) increases. One clinical challenge is to predict, if there is a critical preodontoid interval (AADI) at which intervention should occur. Schmitt-Sody et al. have reported no correlation between AADI and neurological symptoms with no significant change to this radiological parameter following surgery.⁷⁴

Evolving instability within the cervical spine can lead to cranial settling (the migration of the odontoid peg into the foramen magnum) occurring in conjunction with AAS. The detrimental effect of this on the autonomic nervous system in addition to the cerebral blood supply necessitates early detection. A number of radiological measurements have been used to assess patients and identify this abnormality. Kwong et al. have suggested that the McRae line is the easiest to measure as cross-sectional imaging is now the normal format for investigation.⁷⁵ However, the decision on timing of surgery is a controversial one without

a clear direction in the literature. Perhaps predictably greater improvement in symptoms postoperatively has been reported in patients with a lower Ranawat grade preoperatively,⁷⁴ leading to the conclusion that cervical stabilization should be performed prophylactically prior to the presence neurological symptoms.

Subaxial subluxation can occur as part of the pathological process with destabilization of the spine due to involvement of intervertebral discs, facet capsule, and interspinous ligaments or secondary to atlantoaxial fusion. Excessive correction of the atlantoaxial angle and the formation of extensive bony union at C1–C2 following such surgery are risk factors for subaxial disease.⁷⁶ A study examining the correlation between myelopathy and MRI findings appears to demonstrate that subaxial subluxation and subsequent stenosis are better tolerated than atlantoaxial stenosis and are less likely to lead to myelopathy.⁷⁷ However, patients with subaxial disease have a poorer improvement in symptoms after surgery compared to those whose indication was atlantoaxial pathology.⁷⁸

Subcervical spine disease in rheumatoid arthritis has received less attention, although the prevalence of this may be higher than traditionally thought.⁷⁹ In addition, asymptomatic pathology below the neck may coexist with cervical disease or be difficult to distinguish from degenerative spondylosis.^{80,81} The primary pathophysiology in the thoracolumbar spine may be intravertebral or inflammatory degeneration of the endplates.⁸² Surgery is not normally required but vertebroplasty for painful bony collapse can be used,⁸³ and florid thoracic facet-joint synovitis resulting in spinal cord compression has been reported, highlighting the need for full cervicothoracic imaging in patients presenting with myelopathy.⁸⁴

Spinal surgery in patients with rheumatoid arthritis is challenging both for local and systemic reasons. Instrumented fusion and neurological decompression are performed prophylactically to prevent the progression of bony instability or occurrence of myelopathy or therapeutically for pain (mechanical neck pain or C2 radiculopathy), deformity leading to functional deficit or to attempt to prevent neurological deterioration when symptoms of myelopathy are already present.

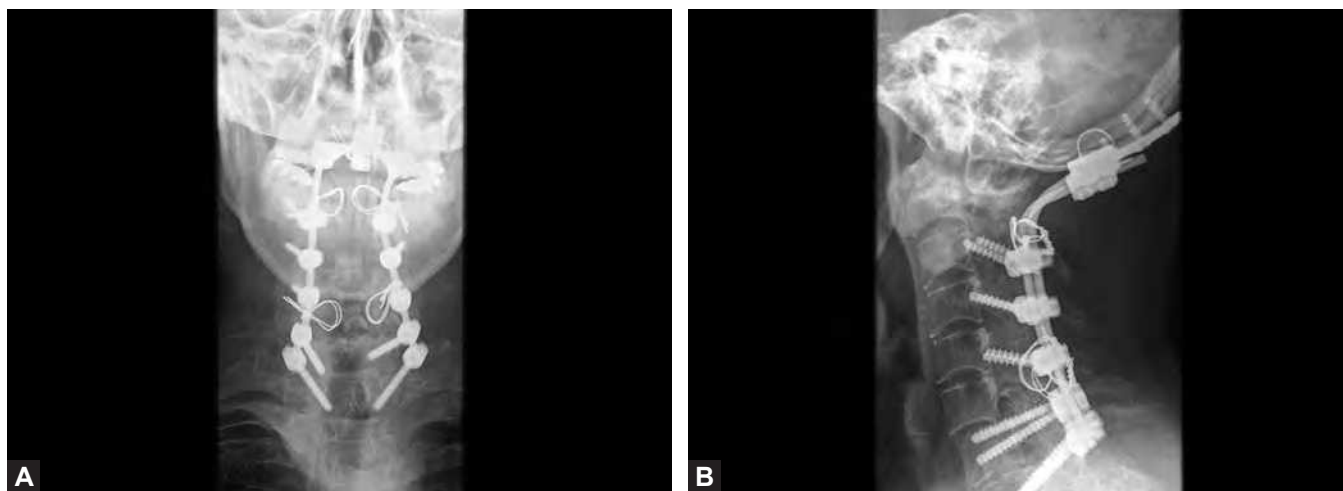
Preoperatively patients need to be assessed by a multidisciplinary team involving surgeons, rheumatologists, anesthesiologists, cardiologists, respiratory physicians, occupational, and physiotherapists. Halo traction prior to surgery can be of benefit. This may allow controlled reduction of deformity in an awake patient and give a better guide to the optimal position in which to place the patient once neurology cannot be so easily assessed under anesthesia.⁸⁵

Anterior (cervical, transoral, or transnasal⁸⁶), lateral, and/or midline posterior approaches to the cervicothoracic spine can be utilized. When a posterior approach is utilized, laminectomies permit decompression of the spinal cord and nerve roots but without stabilization have been reported to lead to a 15–37.5% incidence of instability/kyphosis with subsequent longer-term functional/neurological deterioration.⁸⁷ Multiple techniques are described for stabilization of the occipitocervical (OC) and atlantoaxial segments (Magerl's, Harms) but in common with subaxial spinal surgery, lateral-mass screw/laminar hook and rod constructs are now the most widely used forms of instrumentation.⁸⁸ The aim of all the techniques is to provide early stability to allow a solid fusion to take place and reduce the need for external immobilization. Screw fixation within the bone may be augmented with sublaminar wiring techniques, particularly in view of the higher rate of osteoporosis in patients with rheumatoid arthritis. It is important to consider the overall sagittal balance (an individual's head position in relation to the pelvis) in preoperative planning to aid decision on length of instrumentation and the need to span spinal segment junctions (cervicothoracic/thoracolumbar/pelvic). Grafting techniques with autologous bone, bone substitute, and locally harvested bone (including from the occiput⁸⁹) are all used.

Fusion rates, however, of posterior fusion in patients with rheumatoid arthritis are lower than those with other indications for surgery. Ito et al. with a reported rate of 93% (rheumatoid) and 100% (nonrheumatoid) patients.⁹⁰ As successful union is the major influence on implant failure, it is not surprising that rates of mechanical failure (plate, rod, and screw breakage) are also higher in rheumatoid patients; in a recent study of 142 patients, all such failures except one were in these patients (failure rate 4.2%).⁹¹

Magerl's fusion was the earliest technique described utilizing screws to treat the atlantoaxial segment affected by subluxation. This technique involves bilateral transarticular screws, bone grafting, and traditionally is supplemented by posterior wiring (Figs. 29.2A and B).⁹² This form of instrumentation was a significant advance in terms of achieving solid fusion over the earlier posterior wiring alone described by Gallie among others, which required postoperative halo immobilization. Studies examining the need for sublaminar wires (in addition to transarticular screws) have demonstrated equivalent fusion rates with iliac crest grafting and screws alone.⁹³

The Harms technique of atlantoaxial fusion (C1 lateral mass–C2 pedicle fixation) is an alternative to the Magerl's fusion. A slightly higher fusion rate (97.5% vs 94.6%



Figs. 29.2A and B: Postoperative AP (A) and lateral (B) view following reconstruction.

$p < 0.001$) and lower risk to the vertebral artery (4.1 vs 2% $p = 0.02$) during screw placement are reported on direct comparison of this rod-screw construct to the Magerl's technique.⁹⁴

Preoperative planning with particular reference to CT imaging is essential to ensure the anatomy of the cervical vertebrae, which is often abnormal due to the disease process, as it will permit the surgeon's fusion technique of choice.

There has been a reported trend in the increase of C1–C2 fusions performed in preference to OC fusions for rheumatoid patients with myelopathy and atlantoaxial disease.⁹⁵ Patients have tended to be earlier in the disease process (i.e. less myelopathic) than those treated traditionally with OC fusion but survival rates have improved significantly from 51% (1980–1990) to 81% (2010–2011) with a 9% revision rate of C1–C2 fusions to later OC fusion.⁹⁵ The use of C1–C2 fusion with sparing of the occiput–C1 segment permits the retention of a large amount of anatomical movement and should reduce the risk of subaxial adjacent degeneration. A recent investigation, with a mean follow-up of 9.4 years, has suggested that C1–C2 fusion can be used with a very low risk of degeneration at the OC segment supporting the belief that OC fusion should not be used prophylactically when disease is only radiologically evident at the atlantoaxial (AA) segment.⁹⁶

Posterior decompression and instrumentation may need to be performed in conjunction with anterior decompression by removal of the odontoid peg in cases of basilar invagination from an accumulation of pannus or an abnormally positioned dens. Traditionally, the transoral approach has been used for this but other techniques,

for instance a transnasal, transclival method, have been utilized with success.⁹⁷

Patients with craniocervical or subaxial disease are treated with OC instrumented fusion with “rigid” rod/occipital plate and pedicle/lateral mass screw constructs. An as yet unpublished recent study that analyzes the largest series to date ($n = 100$ OC fusions) has demonstrated significant improvements in neck and myelopathy disability measurements after OC fusion with fusion rates of 70% using radiographic analysis alone; 4% instrumentation failure (metalwork breakage or screw pullout) and a case of improvement from Ranawat 3b to 3a (nonambulatory to ambulatory). This last point is important as traditionally OC fusion was considered to be associated with poor outcome in patients with rheumatoid disease functional status Ranawat.⁷⁴ The significant improvements in medical treatment of rheumatoid arthritis and perioperative care of these patients may mean that the surgical care of such cases with severe disease needs to be reconsidered.⁹⁸

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Operative and Nonoperative Management of Ankylosing Spondylitis

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Snapshot

- » Nonoperative Treatment
- » Medical Treatment
- » Surgical Treatment
- » Acute Spinal Fractures in Patients with Ankylosing Spondylitis
- » Spinal Pseudarthrosis

INTRODUCTION

Ankylosing spondylitis (AS) was first described by the neurologists Strumpell, Marie, and Bechterew in the late 19th century. It was therefore called Marie–Strumpell disease, Bechterew’s syndrome, or rheumatoid spondylitis. This disease is predominant in young men and in those who are positive in HLA (human leukocyte antigen)-B27 test. It has an insidious onset of vague low back pain, and as the disease progresses, pain worsens at late night and early morning, and decreases as the day goes by. Moreover, pain markedly decreases or disappears after complete spinal ankylosis. As the disease progresses, low back pain migrates to upper thoracic and cervical regions and the range of movement of spinal column gradually decreases and eventually becomes bony ankylosis of the entire spinal column. Early radiological changes are superior and inferior corner squaring of lumbar vertebral body, pseudowidening, and erosive changes of the sacroiliac joint. Skeletal involvements besides spinal pathology are hip and shoulder joints, and extraskeletal manifestations include iridocyclitis, aortitis, and cardiac conduction abnormalities.

Spinal involvement results in synovitis, followed by bony ankylosis of facet joint, ossification of anterior longitudinal ligament (ALL), interspinous ligament, and ligamentum flavum. The main treatment in the acute inflammatory

phase is pain control and frequent stretching and exercise to delay joint ankylosis as long as possible while avoiding flexed positioning of the torso. In the established phase, the main treatment objective is to control of fatigue pain due to deformity and to correct the poor posture rather than pain.

NONOPERATIVE TREATMENT

Exercise Role

Several trials have displayed the benefits of physiotherapeutic exercise that include increased spinal mobility and the reduction of functional impairment.¹

MRI is beneficial for early diagnosis due to the ability to detect sacroilitis earlier than alternative forms of radiographic imaging.¹ Additionally, MRI can visualize inflammatory changes of sacroiliac joints earlier than other imaging tools.¹

Biologic Agents

Tumor necrosis factor alpha antagonists have demonstrated the ability to act as disease-modifying agents. These drugs target inflammatory pathways utilized by the immune system that underly the origin of AS and consequently provide significant symptomatic relief.

MEDICAL TREATMENT

At present, the only medication known to suppress bone formation and advance of the disease is nonsteroidal anti-inflammatory drugs (NSAIDs). Of the disease-modifying antirheumatic drugs, which were formerly used, only sulfasalazine is effective in peripheral arthritis, while the rest drugs have uncertain effects and are, thus, not recommended. If treatment with two or more NSAIDs is not effective, biologic agents, such as tumor necrosis factor (TNF) blocker are recommended.

Nonsteroidal Anti-inflammatory Drugs

Nonsteroidal anti-inflammatory drugs, the first treatment choice, are the only medication known to suppress bone formation. They decrease inflammation by suppressing production of prostaglandin, an inflammatory mediator, by suppressing cyclooxygenase in arachidonic pathway. Thus, constant use of NSAIDs theoretically decreases inflammation and bone formation.^{2,3}

Antirheumatic Drugs

Sulfasalazine, methotrexate, etc. are occasionally used, but have fewer effects on spinal symptoms.

1. *Sulfasalazine*: This resolves into sulfapyridine and 5-aminosalicylic acid by colonic intestinal flora. Sulfapyridine suppresses intestinal flora and 5-aminosalicylic acid suppresses inflammation. Taggart et al.⁴ found that sulfapyridine seems to suppress peripheral arthritis by suppressing intestinal flora.
2. *Methotrexate*: It is reported to be effective in a small proportion of patients. It is a purine antagonist and decreases the function of immune cells by suppressing purine that is used in deoxyribonucleic acid synthesis in cell division and proliferation. In rheumatoid arthritis, there is definite evidence of suppression of bone destruction, but the essential mechanism of this suppression is not clear. However, in AS, it is not recommended because the mechanism of disease progression is different.⁵
3. *Biologic agents*: Tumor necrosis factor blocker is an effective drug among biological agents. Infliximab was followed by etanercept, then adalimumab was produced, and new types are being produced. The indication of this agent is a recommendation by a specialist when there is no response to more than two NSAIDs

for >1 month in ASAS (Assessment of Spondyloarthritis international Society) group and four or more points in BASDAI (Bath Ankylosing Spondylitis Disease Activity Index).^{1,6,7} Reactivation of latent tuberculosis can occur often; thus, prevention and examination for tuberculosis is essential.⁸

These TNF-blocker agents show outstanding effectiveness in patients' pain, range of physical activities, quality and function of life. However, whether it changes the course of disease progression is not certain yet.

4. *Glucocorticoid*: The efficacy of systemic steroids is not yet evaluated in clinical studies. However, patients with AS are not recommended for this because they already have severe loss of bone density.⁶

SURGICAL TREATMENT

The main presenting clinical problems related to the spine in established phase are gross fixed kyphotic deformity, acute spinal fracture, and spondylodiscitis. Andersson lesion (AL) is a destructive vertebral caused by minor trauma that occurs in the late stage of the ankylosing spondylitis.⁹

Deformity

The loss of lumbar lordosis or increased thoracic kyphosis seen in patients with AS can result in severe sagittal deformities. And the patients with AS usually have limited neck motion. These kyphotic deformities may restrict the daily activity. In severe kyphotic deformities, there may be decreased function of gastrointestinal system and poor hygiene. The cause of kyphosis is uncertain but possible causes may be positional to reduce the pain, gravity, and a slight flexed position in daily activity, etc.

Corrective osteotomy could alleviate not only clinical problems, but also social problems including restricted horizontal gaze and self-image.¹⁰⁻¹² Various correction methods had been introduced since 1945 when Smith-Petersen first performed.¹³ However, these methods were less popular because of high risk of complications.

In 1963, Scudese¹⁴ first described a lumbar wedge osteotomy in AS and this procedure had become popular by Thomasen.¹⁵ Now this procedure is called pedicle subtraction osteotomy or egg-shell osteotomy. Most of AS patients can be corrected by this method. In 2013, Kim et al. introduced a modified technique of this method as partial pedicle subtraction osteotomy.¹⁶

In severe kyphotic deformity, vertebral column resection (VCR) can be used. This was first described in 1922 by MacLennan¹⁷ and was performed by the posterior-only approach. This procedure was performed with anterior and posterior approaches by Luque¹⁸ and Bradford.¹⁹ In 2002, Suk et al.²⁰ developed the posterior-only approach for vertebrectomy attempting to reduce operation time and complication.

Surgical Planning

When to Operate?

Due to sagittal imbalance of the spine and osteoporosis, pathological fractures can occur in patients presenting with AS. The formation of pseudoarthrosis and fracture can progressively increase kyphotic deformity commonly resulting in nerve dysfunction. Surgical intervention is the only approach that can relieve chronic back pain while simultaneously correcting kyphotic deformity.²¹

When Lumbar PSO?

Lumbar pedicle subtraction osteotomy (PSO) is recommended for the treatment of large sagittal deformities that measure more than 25° of rigid loss of lordosis.

Additionally, PSO correction should be performed at an angle of approximately 30°, which is performed mainly at the lumbar level. Cases presenting with a substantial sagittal imbalance of >10 to 12 cm with a sharp, angular kyphosis are ideal for this approach.²²

When Cervical PSO?

Currently, the only report of PSO in the cervical spine occurred at C7. Due to the location of the apex of the cervical kyphoscoliosis at C6, the PSO was performed at C6.²³

Whether to do Hip or Spine First?

Initially correcting hip joint deformity and adjusting limited range of motion of the hip can play a critical role in planning the degree of spinal deformity correction in patients with severe AS.²³

Perioperative Consideration

Prior to a spinal osteotomy, a careful neurological examination of the patients is essential, even though neurologic deficit is very rare in AS. The somatosensory-evoked potential, motor-evoked potential (MEP), real-time

electromyography, and a wake-up test should be prepared to monitor any changes in the patient's neurological status at the start of the operation, during the procedure, and after correction of the deformity.

It can be difficult to perform endotracheal intubation in cases, in which neck motion may be limited in a flexed position. Therefore, bronchoscopic or tracheostomic intubation might be necessary. Accordingly, a collaborative approach with an anesthesiologist is important. In case of severe flexion deformity of trunk, hip joint flexion contracture, it is very difficult to get prone position. In these cases, operation table should be flexed to fit the patients and multiple pads should be prepared. Occasionally, there may be situations where a table should undergo flexion or extension to achieve deformity correction. For this reason, an electrical motored table that can undergo flexion or extension should be prepared.

If a patient with severe flexion deformity and rigid ankylosis of the cervical spine is operated upon in the prone position, extreme care is needed to ensure that the head is kept clear of the table and does not take any of the body weight. Otherwise, the neck may be fractured or dislocated when an extension force is applied to the spine. During the procedure, the patient's head supporter might be moved, which can exert direct pressure to the eyeballs and induce an occlusion of the retinal artery, potentially leading to blindness.

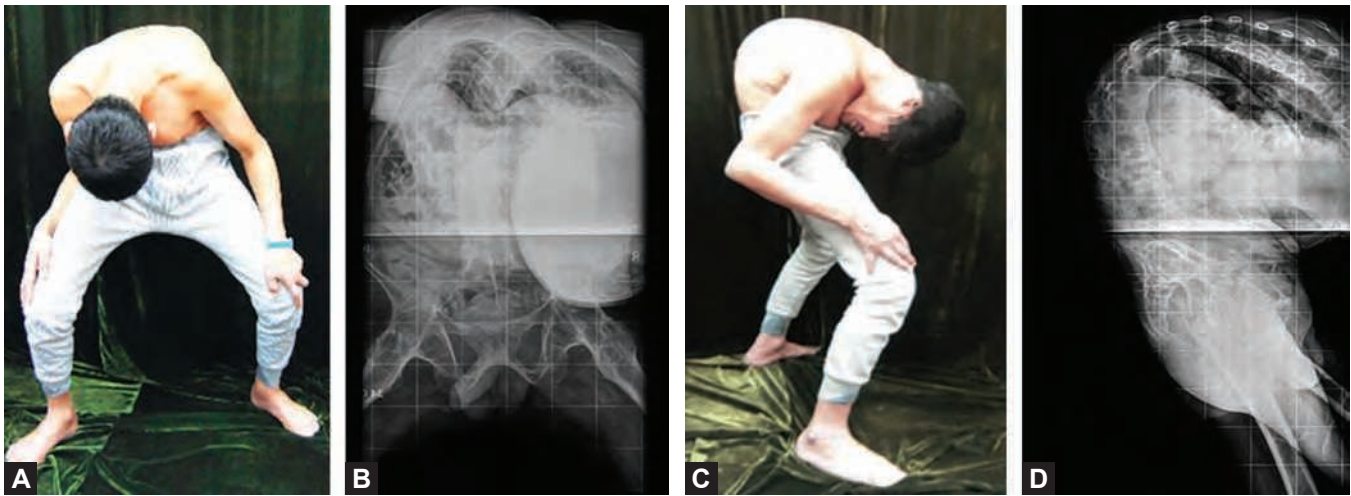
Sometimes, acute dilatation of the stomach, paralytic ileus, or, in rare cases, superior mesenteric artery syndrome can occur after spinal osteotomy because an abrupt extension occurs from a flexed position. In these cases, nasogastric or rectal tube insertion may be needed during a certain period of time after surgery.²⁴

Osteotomy

The ideal site to perform osteotomy is at the apex of deformity. However, anatomical characteristics of each region should be considered, and the safest and most effective location should be chosen. We have to consider vertebral artery in cervical, cord, and rib cage in the thoracic region, and root level and long lever arm from the osteotomy site to head the in lumbar region (Figs. 30.1 and 30.2).

Thoraco-osteotomy or Lumbar Osteotomy

1. *Surgical technique of Smith-Petersen osteotomy (SPO):* The level chosen for the osteotomy is determined by the lowest degree of ossification anteriorly and the apex of the deformity. In the prone position, pedicle screws



Figs. 30.1A to D: (A) Global kyphotic deformity of the spine showing (B) “chin-on-pubis” deformity of the patient. The chin-brow vertical angle was fixed at 140° . The activities of daily living were severely restricted. Simple (C) anteroposterior and (D) lateral radiographs revealed complete bony ankylosis in which the bones that included the skull and all vertebrae, and both sacroiliac and hip joints were fused into a single bone. The sagittal plane deformities had kyphosis angles of 40° in the cervical spine, 115° in the thoracic spine, and 15° in the lumbar spine.

are inserted from the upper instrumented vertebra to the lower instrumented vertebra. The initial resection is performed on the spinous process at the level to be resected. Portions of the spinous processes above and below the level should also be removed. In the area to be resected, lamina and facet joints are removed completely using an osteotome or Kerrison rongeur in an oblique shape. A gutter is formed as a V shape from the center bilaterally to the oblique directions on the upward and lateral sides. In particular, on the lateral end, the structure between the upper and lower pedicles should be removed completely to prevent nerve root impingement. Commonly, the width of the gutter should be 10–15 mm. After the formation of the gutter, it is closed posteriorly by manual compression and a push down force with a compression device on both sides or extending the operation table. Special care should be taken to undercut the margin of osteotomized lamina in order to avoid neural compression during closure. The rods are then set and decortication with an autogenous morselized bone graft is applied over the entire levels of the corrected segments. By this technique, average correction can be achieved up to 10° – 15° in each segment. Also in the case of fully ossification of ALL it is very difficult to open the ALL during correction.

2. *Surgical technique of pedicle subtraction osteotomy (PSO):* Pedicle screws are inserted into two or three

segments above and below the pedicles to be resected. After identifying both pedicles to be resected, holes are made through the pedicles into the vertebral body. Curettes are used to increase the size of the pedicle holes. The transverse processes are excised at their bases. Using angled curettes, the cancellous bone in the body is pushed anteriorly into the body to create a cavity in the vertebrae. Laminectomy and facetectomy are performed. The posterior and lateral part of the body is decancellized with angled curettes and both pedicles are enucleated with small osteotome. After thinning the posterior and lateral cortical walls with curettes, the posterior cortex of the vertebral body is pushed down into the body. With firm grasping of the cranial and caudal spinous processes with towel clamps, the operating table is extended, gradually closing the osteotomy. Pedicle screw stabilization is performed after confirming that the exiting nerve roots are free. The spinal cord function is monitored continuously by the MEP. The average correction angle is 25° – 40° in each vertebra by this method.

3. *Surgical technique of VCR:* It can be performed either through a combined anterior and posterior approach or through a posterior-only approach. This chapter describes the procedure through the posterior-only approach.

Like other osteotomy techniques, pedicle screws are placed segmentally, except for the resected segments.



Figs. 30.2A to F: (A) Preoperative and (B) postoperative photographs of the patient during cervical pedicle subtraction osteotomy at C6. A correction angle of 45° was achieved. Prone position (C) before posterior vertebral column resection and (D) intraoperative photographs of posterior vertebral column resection on T11 and T12. (E) A clinical photograph and (F) a whole spine standing lateral radiograph at the last follow-up. Correction angles were 45° , 70° , and 30° in the cervical, thoracic, and lumbar spines, respectively, without neurological complication. Excellent improvement of activities of daily living with horizontal gaze was achieved with 10° of chin-brow vertical angle.

Complete exposure should be done to both transverse processes to allow easier removal of the vertebral bodies. If the segments to be resected are located on the thoracic

spine, costotransversectomies should be performed to exposure the vertebral body. The posterior components (spinous processes, lamina, and facet joints) should be

completely removed to the level of the segments that need to be removed. Both pedicles are then removed using an osteotome. During this procedure, the nerve roots should be saved in lumbar spine. However, in thoracic spine, the nerve roots can be sacrificed because these are intercostal nerves. Osteotomy of the vertebral body is performed on either side of thecal sac. Bone resection should be wedged in sagittal plane and may be asymmetric or symmetric in coronal plane to correct kyphosis and scoliosis components. The bone should be removed completely to ensure that anterior cortical breakage should occur. Before the procedure for the contralateral side, fixation should be performed using a temporary rod. The same procedure should then be performed for the contralateral side. A structural autograft, structural allograft, or metal cage should be used for the reconstruction of bone defect. Using the middle column as a hinge, the anterior part undergoes slight lengthening and the posterior part undergoes shortening to obtain the largest possible amount of correction. It is also important to minimize the changes in the length of the middle column at the cord level. Once a deformity correction is complete, connecting between the pedicle screws and rods is performed. To avoid nonunion or pseudarthrosis, we try to minimize the extent of bony defect by bone-on-bone contact. However, in cases of inevitable bony defect, it is covered with a thin rectangular shape autologous bone graft. Then, abundant morselized bone graft is applied after decortications with a gauge or a burr.

Cervical Osteotomy—Technique

Corrective osteotomy of the cervical spine is one of the most challenging procedures because of catastrophic complications, such as irreversible spinal cord injury and possible brain damage from a vertebral artery injury. This procedure is considered riskier than thoracolumbar osteotomy. Urist²⁵ reported the first case of corrective osteotomy for the cervical spine in 1958, an extension osteotomy similar to the SPO of the lumbar spine. He recommended the C7/T1 junction as the optimum site for corrective osteotomy because (1) the spinal canal is relatively wide, (2) the cervical cord and eighth nerve root have good flexibility in this region, (3) damage to the C8 nerve root is less detrimental to the hand function than damage to the other nerve roots, and (4) the vertebral artery is less likely to kink when the neck is extended. Simmons et al.^{26,27} reported the largest series of clinical outcomes after extension

osteotomies in the seating position with local anesthesia and halo fixation. With the development of modern anesthesia, neuromonitoring, internal fixation, cervical spine osteotomy in the prone position—using strong internal fixation and somatosensory-evoked potential and/or MEP monitoring under general anesthesia—is considered a standard procedure in many reports.²⁸⁻³⁰

Osteotomy technique has advanced continuously as well. Conventional extension osteotomy has the largest number of reports and cases.^{26,28,29,31-34} These articles reported excellent clinical outcomes but a non-negligible rate of complications as a result of the loss of correction and related neurological complications. In 2002, El Saghir and Boehm³⁵ reported that corrective osteotomy consists of posterior osteotomy after an anterior release. Mummaneni et al.³⁶ reported a similar anterior-posterior-anterior 540° procedure to allow for safer correction with structural stability.

Most recently, a closing osteotomy technique on C7 using the pedicle subtraction procedure for the cervical spine was reported by Tokala et al.³⁷ in 2007. Similar to PSO on the thoracolumbar spine, PSO on the cervical spine has the advantages of structural stability and a wider cancellous contact surface for bony union over the extension-type osteotomy.

ACUTE SPINAL FRACTURES IN PATIENTS WITH ANKYLOSING SPONDYLITIS

Several studies have been shown patients with AS to have a fourfold fracture risk compared to general population and the lifetime incidence ranges from 5 to 15%.³⁸⁻⁴¹ Stress shielding, immobility, and increased bony resorption also contribute to osteoporosis as the disease progresses. Ossification of longitudinal ligament, calcification of the annulus fibrosus, and ankylosis of facet joints make a spine rigid, brittle beam with long lever arms reducing the ability to absorb energy from trauma.⁴²⁻⁴⁵ Global kyphosis may induce an impaired balance with gait disturbance and loss of horizontal gaze. So, AS patients have an increased risk of falling.

Hyperextension injury comprises ~75% because pre-existing kyphotic deformity is more susceptible to extension force. Other patterns are flexion, rotation, and compression. Most fractures occur in the subaxial cervical spine and cervicothoracic junction (81.2%), with C5–C6 and C6–C7 as the most common level.⁴¹ Oblique orientation of junctional facet joint and small-sized cervical vertebra carrying



Figs. 30.3A to C: A 44-year-old woman diagnosed with ankylosing spondylitis slipped down while taking a bath. She used to have difficult anterior vision due to kyphotic deformity. She complained of pain in the back after trauma and had tenderness around thoracolumbar junction without any neurologic deficits. (A) Lateral radiographs and (B) 3D-CT show bony ankylosis of the spine with wedge-shaped fracture gap between L1 and L2 and pseudarthrosis at L3 and L4. We performed transpedicular wedge resection osteotomy on T12 and L1 to obtain fracture fixation and simultaneous deformity correction. A cage with massive bone graft was inserted between the gaps for bony union. After 6 months, the patient has improved in anterior vision with improved kyphosis and (C) she was painless as the X-ray shows fracture site united well (3D: Three-dimensional; CT: Computed tomography).

the head weight are the main reasons.^{46,47} Thoracolumbar fractures, mostly happen at the thoracolumbar junction area, are significantly less common than in the cervical region. Neurologic deficit risk ranges from 33 to 50% and is relatively low compared to cervical fractures.^{42,48} Most fractures are also highly unstable.

Fractures in AS have a high risk of neurologic complications. One study reported that about two thirds of patients have a spinal cord injury at initial presentation. This is ~11 times higher than the general population.⁴⁹ About one third of patients had delayed diagnosis caused by the patient or the physician. Pre-existing axial pain indistinguishable from fracture pain and low-energy impact mechanism cause patient delays.^{50,51} Difficult plain X-ray findings at the cervicothoracic junction could be a missed diagnosis by the physician.⁵² So physicians should have special awareness with high index of suspicion to AS patients with ambiguous symptoms even after minor trauma.

Any patient of AS presenting with pain in the neck or back following trauma, however trivial it may be will need evaluation by CT scan, X-ray, & Ct scanMRI pictures pictures

Nonoperative treatment is not suitable for fracture patients because most fracture patterns are unstable with long lever arm and three-column involvement. Although

there may be no neurologic deficit and deformity, secondary neurologic deficit with delayed dislocation happens in ~60% of patients. Infection, skin ulceration, fracture malunion, and pulmonary impairment could all occur with conservative treatment.⁴² Surgical treatment is also indicated in cord compression with neurologic deficit, neural compressive epidural hematoma, and spinal deformity.^{43,53,54} Using axial traction to get realignment, gentle traction with 5–10 pounds is important. Overdistraction may occur well due to instability and paraspinal muscle deconditioning.⁵⁵ Surgical positioning is the most important and critical point. Intraoperative positioning should be adjusted with pre-existing kyphotic deformity using proper support in all regions (Figs. 30.3A to C).

Surgical approach is dependent on fracture locations and patterns. Due to the frequency of cardiopulmonary co-morbidities in AS patients, the likelihood of complication or morbidity increases when using an anterior-posterior approach. For fractures of the lower cervical spine, lateral mass screws up to the C-3 level can be used, and in certain cases, pedicle screws at the C-2 level may be necessary. When reconstruction spans the cervicothoracic junction, thicker rod diameter and materials should be evaluated to ensure stability.⁵⁶

SPINAL PSEUDARTHROSIS

A “bamboo spine” appearance resulting from syndesmophyte formation is typical in advanced AS patients. Although less common, destructive lesions of the intervertebral disc and vertebral body are also found in AS. The pathophysiology, natural history, and even the terminology of this lesion in AS have been controversial.

These lesions were reported in 1937 by Andersson.⁵⁷ Since then, several reports have described these lesions differently. The term “spondylodiscitis,”⁵⁸⁻⁶⁰ which implies inflammatory etiology, was used by some authors. Although the cause of these lesions was initially unclear, other authors described them as “destructive vertebral lesion”⁶¹⁻⁶⁴ or “spinal pseudarthrosis.”^{65,66}

Possible mechanisms for the formation of pseudarthrosis have been suggested. First, since spinal ossification in AS may not be contiguous, the skipped segments that have not completely ossified are exposed to increased stress due to the long ankylosed segments. The mechanical stresses may cause increased wear at the discovertebral junction, followed by fibrous repair. Kim et al. reported that a history of trauma or an inflammatory reaction was not present in all AS patients with pseudarthrosis, although they might be found occasionally.⁶⁷

Although a few AS patients who had spinal pseudarthrosis remained asymptomatic, spinal pseudarthrosis in AS may occur with sagittal plane deformity and may cause severe pain and neurologic symptoms from fibro-osseous tissue proliferation around the lesion.^{65,66} The kyphotic deformity associated with AS results in increased gravitational stress concentration at the pseudarthrosis site between the long lever arms. In 1984, Simmons and Goodwin⁶⁰ described the high incidence of pseudarthrosis in kyphotic patients and attributed it to the severity of deformity. Most authors have reported the thoracolumbar segments as the most frequent site of pseudarthrosis. As the thoracolumbar segments are subjected to the highest stress in the kyphotic spine, the mechanical theory of pseudarthrosis has been supported. The operative findings of spinal pseudarthrosis proliferated osteophytes and fibrotic tissues around pseudarthrosis, which had been ossified and adhered to neural tissues to variable degrees. Sometimes there could be dural defect around pseudarthrosis.

When to Conserve and When to Operate?

It is widely accepted that operative treatment should be highly considered when there is a lack of stability of the spine, or when neurological impairment exists.⁶⁸

Posterior Only Stabilization

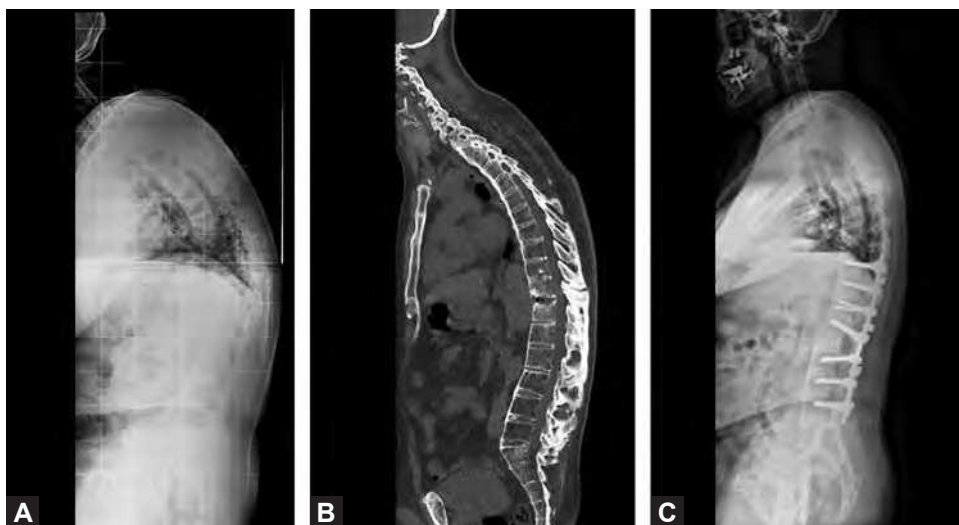
Posterior stabilization can provide benefit to patients who present with traumatic fractures that maintain preservation of alignment across the fracture site. Accurate lateral mass plating above and below the fracture is critical for successful fixation and fusion when using the posterior approach.⁶⁹

Posterior and All Posterior Reconstruction

Surgical treatment of pseudarthrosis in AS patients should be focused on stabilization and sagittal realignment. In cases with kyphotic deformity, Smith-Petersen type osteotomy could be considered. After posterior closing of both ends of osteotomy, a bone defect was almost absent or very less, and the amount of the local bone was adequate for posterior fusion. Anterior interbody fusion (AIF) for pseudarthrosis allows for repair of the lesion, including complete curettage and bone grafting. Surgical repair of pseudarthrosis with AIF provided successful fusion and good clinical results. For patients with lumbar hypolordosis, additional PSO was effective in restoration of sagittal balance (Figs. 30.4A to C).

KEY POINTS

- Prior to operation in AS, a thorough understanding of the anatomy of the adjacent structures, such as the neural structure, visceral structure, and spinal column, as well as sufficient surgical technique are essential. In addition, consideration of the myriad of potential complication that might occur is important. Therefore, well-organized teamwork with other departments including the anesthesiology, internal medicine, neurology and rehabilitation is indispensable.
- Nonoperative treatment is not suitable for fracture patients in AS because most fracture patterns are unstable with long lever arm and three-column involvement. Secondary neurologic deficit with delayed dislocation happens in ~60% of patients with conservative treatment. Surgical treatment is also indicated in cord compression with neurologic deficit, neural compressive epidural hematoma, and spinal deformity.
- Surgical repair of pseudarthrosis with AIF provides successful fusion and good clinical results. For patients with lumbar hypolordosis, additional PSO is effective in restoration of sagittal balance.



Figs. 30.4A to C: A 53-year-old man complained pain in the thoracolumbar junction. He was diagnosed with ankylosing spondylitis 7 years ago. Radiologic examination shows global kyphotic deformity and pseudarthrosis between (A) T11 and (B) T12. (C) We performed PSO on L2 and anterior support with bone graft on T11–T12 via left side extrapleural approach after 10th rib removal. PSO, pedicle subtraction osteotomy.

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SECTION

4

Bone Grafting

Luiz R Vialle

Techniques and Complications of Bone Graft Harvesting

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Snapshot

- » Current Graft Options
- » Surgical Techniques

- » Complications

INTRODUCTION

With the advancement of biologics and new bone biomaterials, as well as new data challenging many of the established notions of nonlocal autograft, the subject of bone graft harvesting has become an increasingly controversial topic of discussion. While the use of iliac crest-harvested autograft remains the gold standard, the trend of investigating alternatives has persisted, with a rapidly growing body of literature. New data have emerged in recent years challenging the traditional understanding of nonlocal autograft harvest and associated complications thereof. This chapter presents a review of the techniques and complications of bone graft harvesting, as well as a discussion of the most recent literature on the subject.

CURRENT GRAFT OPTIONS

Autologous Bone Graft

Nonlocal autograft is most frequently harvested from the anterior or posterior iliac crest, although alternative options exist with specific indications.

Iliac Crest

Iliac crest bone graft (ICBG) remains the gold standard because of the unparalleled combination of osteoinductive, osteogenic, and osteoconductive properties,¹⁻⁴ as well as its porosity that helps to promote graft vascularization.

In addition, its ease of harvest from both the anterior and posterior crest, as well as its versatility of use as either a cancellous or cortical graft, allows ICBG to be applied in virtually any fusion surgery. The anterior crest is preferred in cortical applications as the graft may bear much higher axial loads,⁵ while the posterior crest is the preferred source for cancellous graft due to a larger volume of harvestable cancellous bone.⁶

Local

Local autograft obtained from the laminectomy portion of posterior lumbar fusion has been increasingly used in these procedures. The fusion rate with the use of local bone graft in posterior lumbar procedures has been shown to be equivocal to ICBG,⁷⁻⁹ and the volume of local graft harvestable in a single-level fusion is similar to that which can be obtained from the posterior iliac crest.¹⁰

Fibula

Bone graft harvested from the fibula is notable for the large cross-sectional area of cortical bone and the biomechanical stability, and is most commonly indicated in cervical reconstruction following anterior corpectomy. However, because fibular graft lacks many of the osteogenic properties found in cancellous bone, its harvest is frequently deferred in favor of allograft bone or titanium mesh cages in conjunction with cancellous autograft.

Rib

Rib autograft is rarely used, with the exception being when it is harvested as part of the transthoracic approach to the spine, during which time a section of the rib may be removed to improve exposure.

Intramedullary

The reamer-irrigator-aspirator (RIA) system was developed by Synthes in the 1990s in an attempt to reduce intramedullary pressure when reaming for intramedullary nail fixation of the femur and tibia.¹¹ In the mid-2000s, however, experimentation led to the practice of using the system for harvesting intramedullary bone graft, by running the aspirate through a sterile filtration system.^{12,13}

While data are limited, early studies have shown that intramedullary harvest allows surgeons to obtain similar volumes of bone graft as that reported for posterior ICBG, with similar harvest times and a lower rate of major complications.^{14,15} In addition, intramedullary and ICBG share similar transcriptional profiles for genes related to bone formation and repair,¹⁶ as well as for the presence of viable osteoprogenitor cells.^{17,18} Intramedullary graft material was also found to have a greater occurrence of mesenchymal stem cells¹⁶ and colony-forming fibroblasts,¹⁹ which may indicate a more favorable osteogenic and osteoinductive profile. While large-scale clinical trials are needed to determine the efficacy of intramedullary bone grafting for spinal fusion procedures, early case reports in the literature show promise for this application.²⁰

Allogenic Bone Graft

In most series the fusion rates when using allograft, either with or without autograft, are lower than when using autograft alone.²¹⁻²³ However, fresh-frozen cortical allografts have been shown to perform significantly closer to autograft than freeze-dried material, despite the increased immunogenicity and delayed incorporation.²⁴⁻²⁷

SURGICAL TECHNIQUES

Anterior Ilium

There are four techniques of graft procurement from the anterior iliac crest, each with unique advantages and disadvantages.

Tricortical Graft

Tricortical grafts are preferentially obtained from the anterior iliac crest. A direct approach may be used, where

the skin is incised over the crest and the muscular attachments to the inner and outer walls of the ilium are dissected away using periosteal elevators. Additionally, when a retroperitoneal or thoracoabdominal approach to the spine is used, the iliac crest can be reached via subcutaneous dissection over the abdominal wall muscles in order to avoid an additional incision. It is better to opt for an oscillating saw over an osteotome for procuring the graft, as the use of an osteotome has been shown to cause microscopic stress fractures that may weaken the axial strength of the graft.²⁸

Subcrestal Window

The subcrestal window technique allows for the procurement of bicortical graft while leaving the roof of the anterior iliac crest intact. A similar approach is employed as with the tricortical graft, with subperiosteal dissection performed over the preferred region. After appropriate exposure, a straight osteotome or oscillating saw is used to cut the desired section of the bone from laterally to medially, after which the bicortical graft may be removed.

Trapdoor

The trapdoor technique is used when cancellous graft is desired from the anterior approach. Dissection along the medial wall of the ilium is deferred, while a straight osteotome is driven through both walls of the ilium, immediately inferior to the edge of the lateral crest. The periosteum and fascial attachments deep to the medial wall are left intact, and the superficial section of the crest is opened, allowing the medial soft tissues to behave as a hinge. Cancellous bone is obtained via curettage, after which the iliac crest is closed and the lateral fascial layers are reapproximated.

Trephine Method

Trephine curettage can be employed for both the anterior and posterior ilium as a minimally invasive method for obtaining small volumes of bone graft while minimizing postharvest pain. Many variations of this technique have been described in the literature; however, in the majority of cases dissection to the superior edge of the iliac crest is performed, after which a trephine is engaged through the iliac crest between the inner and outer iliac tables. Larger quantities of graft may be harvested by adjusting the angle of insertion of the trephine while remaining parallel to the inner and outer tables of the iliac crest.²⁹⁻³²

Posterior Ilium

Harvesting from the posterior ilium allows for the collection of significantly larger quantities of cancellous autograft, ideal for posterior lumbar arthrodesis. Subcutaneous dissection toward the crest may be performed, if the primary surgical incision is within close proximity. When this is not feasible, a more vertically oriented incision is made 2–3 cm from the midline. This position avoids interrupting the superior cluneal nerves, which course longitudinally, and may pass within 8 cm lateral to the posterior superior iliac spine.³³ A periosteal elevator is used to separate the muscular attachments from the outer table of the ilium, providing clear visualization of the cortex.

To obtain uniform corticocancellous strips, a straight osteotome is employed to make parallel unicortical cuts, perpendicular to the iliac crest along the outer table of the ilium. A curved osteotome may be used to complete the distal and proximal extent of the harvest by connecting the edges of the unicortical cuts in a perpendicular fashion. A straight or curved osteotome is then placed on top of and parallel to the crest, and driven distally in order to unroof the demarcated corticocancellous strips. Gentle tapping of the mallet and careful angulation of the osteotome is essential throughout this harvest in order to avoid violating the inner table of the pelvis. After the corticocancellous strips have been mobilized, the remaining cancellous bone is easily visualized and may be harvested with the use of curettes.

Intramedullary

The technique for intramedullary bone graft harvesting has been well described in the literature,^{13,15,16,34–37} and is very similar to that used for reaming for intramedullary nail placement. The femur is the most frequently harvested bone, and may be approached from either an anterograde or retrograde approach. Patients are positioned supine and fluoroscopy is utilized along with a radiopaque ruler to estimate the diameter of the inner medullary cavity at the isthmus of the femur. Standard minimally invasive entry into the femoral canal is performed until the canal is opened with a cannulated drill and a ball-tipped wire guide is inserted into the femur. At this point, the reamer head size is selected with a diameter 2–3 mm larger than the canal diameter measured at the isthmus, and is gently directed through the femur. Because the RIA has a very sharp cutting head, frequent fluoroscopic checks are necessary to ensure that the cortex is not being reamed

asymmetrically. Reaming is stopped and the sterile filter apparatus attached to the reaming system is emptied when full or when the desired volume of graft material is obtained.

■ COMPLICATIONS

Iliac Crest

Pain

One of the most well-known sequela of ICBG harvest is chronic postoperative donor site pain. While this issue is heavily discussed throughout the literature, there is currently a lack of level-one evidence to adequately quantify it.^{38,39} The traditional understanding of this complication held that chronic pain was extremely common;⁴⁰ however, more recent evidence has shown that this view may be an overestimate.^{41–43}

While the underlying reason for chronic donor site pain of the iliac crest is poorly understood, several options exist for decreasing the likelihood of this adverse event. In some studies, a direct infusion of local anesthetic into the donor site for up to 48 hours after the procedure significantly reduced postoperative pain, even years out from surgery.^{44,45} However, these findings are not without contestation, as other studies have failed to show long-term differences in donor site pain with this intervention.⁴⁶ Further research is necessary to evaluate the true benefit of local anesthetic infusion. The infusion process itself appears to be very well-tolerated, with no reports of long-term complications secondary to its use.

Additional measures may be taken to decrease perioperative and postoperative pain, including a plane block of the L1 dermatome, where local anesthetic is infiltrated into the plane between the transversus abdominis aponeurosis and the transversalis fascia.⁴⁷ For tricortical grafts, reconstruction of the iliac crest defect with either additional segments of local tricortical bone, or with ceramic composite biomaterials, has been shown to be highly effective at decreasing long-term donor site pain.^{48,49}

Arterial Injury

The most common bleeding complication in ICBG harvest is caused by violation of the superior gluteal artery. This artery originates as the largest branch of the internal iliac artery and exits the greater sciatic foramen, traveling in close proximity to the edge of the sciatic notch before extending caudally to supply the gluteal muscles. During

posterior harvest of corticocancellous strips, driving an osteotome too forcefully may cause it to enter the sciatic notch, lacerating the superior gluteal artery and resulting in a brisk bleed.

Repair of the superior gluteal artery can be extremely challenging due to poor visualization of the injury. As the sciatic notch is not easily accessible from an incision made at the posterior iliac crest, it may be challenging to achieve adequate visualization while attempting to repair the defect. Additionally, when a complete transection of the artery occurs, the proximal segment may retract deep to the sciatic notch, requiring a more aggressive dissection. In such a situation, dissection of the superior portion of the sciatic notch is an appropriate maneuver in order to obtain adequate visualization of the artery. The artery should be clearly visualized before clamping or ligation is attempted, due to its close proximity to the ureter and the superior gluteal nerve.

This complication emphasizes the importance of maintaining control of the osteotome at all times, and using gentle taps of the mallet when making parallel cuts into the outer table.

During anterior harvest, aggressive subperiosteal dissection of the inner table may violate the arterial plexus supplying the iliacus muscle. However, due to its easy accessibility and highly anastomotic nature, this arterial injury is typically easier to manage and results in significantly lower patient morbidity than a superior gluteal artery injury.

Nerve Injury

The superior gluteal nerve courses along the gluteal artery, and should be avoided in a similar fashion during posterior harvest. Injury to the gluteal nerve can denervate the tensor fasciae latae, gluteus minimus, and gluteus medius, the latter of which results in the classic Trendelenburg gait.

The superior cluneal nerves, which supply much of the sensory innervation to the buttock, traverse the posterior iliac crest within 8 cm lateral of the posterior superior iliac spine, and may be injured when the posterior incision is continued to this lateral location.

While arterial injury is less common during harvesting of the anterior crest, nerve injury is proportionately more common, often related to aggressive retraction of inner table muscles during the initial dissection, although this is infrequently reported.⁵⁰ The ilioinguinal and iliohypogastric nerves are rarely injured in isolation, and both originate from the lumbar plexus and course laterally in close proximity to the psoas and quadratus lumborum muscles

before perforating the transversus abdominis near the anterior portion of the iliac crest. Injury to these nerves can manifest as a neuralgia consisting of lancinating pain and hyperesthesia or hypoesthesia of the skin along the inguinal ligament and extending from the surgical incision laterally into the inguinal and suprapubic regions.

The femoral nerve and lateral femoral cutaneous nerve (LFCN) also pose a risk for injury during anterior crest harvest, as they travel along the iliacus muscle before exiting the pelvis by coursing deep to the inguinal ligament. Excessive retraction of the inner table components or penetration of the iliacus muscle by an osteotome may cause injury to either of these nerves. Additionally, the course of the LFCN can vary in 10% of individuals in which it exits the pelvis by traversing the iliac crest, rather than diving medially and deep under the inguinal ligament (Fig. 31.1). For this reason, the anterior crest should never be harvested within 2 cm of the anterior superior iliac spine (ASIS).

Other Complications

Stress and avulsion fractures of the ilium are most frequently associated with full thickness grafts from the anterior crest, although there is still a concern for fracture complications in partial thickness grafts, especially in at-risk patient populations, such as those with severe osteoporosis.⁵¹ Avulsion fractures occur most often when tricortical graft is harvested in close proximity to the ASIS, after which the muscular attachments may cause this bony prominence to avulse.⁵²⁻⁵⁴ This, in addition to the previously discussed anatomic variant of the LFCN, further supports the impetus to give a wide berth to the ASIS when harvesting tricortical graft from the anterior crest.

During the harvest of posterior corticocancellous strips, the posterior ligamentous complex supporting the sacroiliac joint may be compromised, resulting in sacroiliac instability that frequently manifests as complex lower back pain that may radiate into the groin, buttocks, and leg. When performing posterior corticocancellous harvest, standing on the opposite operative side of the table from the harvest site directs the osteotome away from the sacroiliac ligamentous complex and decreases the chance of injury to this anatomic structure.

While the iliacus and the abdominal wall muscles serve to protect the peritoneum from violation (and subsequent herniation of abdominal viscera), herniation following iliac crest bone harvest is a potential complication. While the true incidence is unknown, it has been reported in the literature to range from 5% to 9%.^{55,56} Bowel is the most

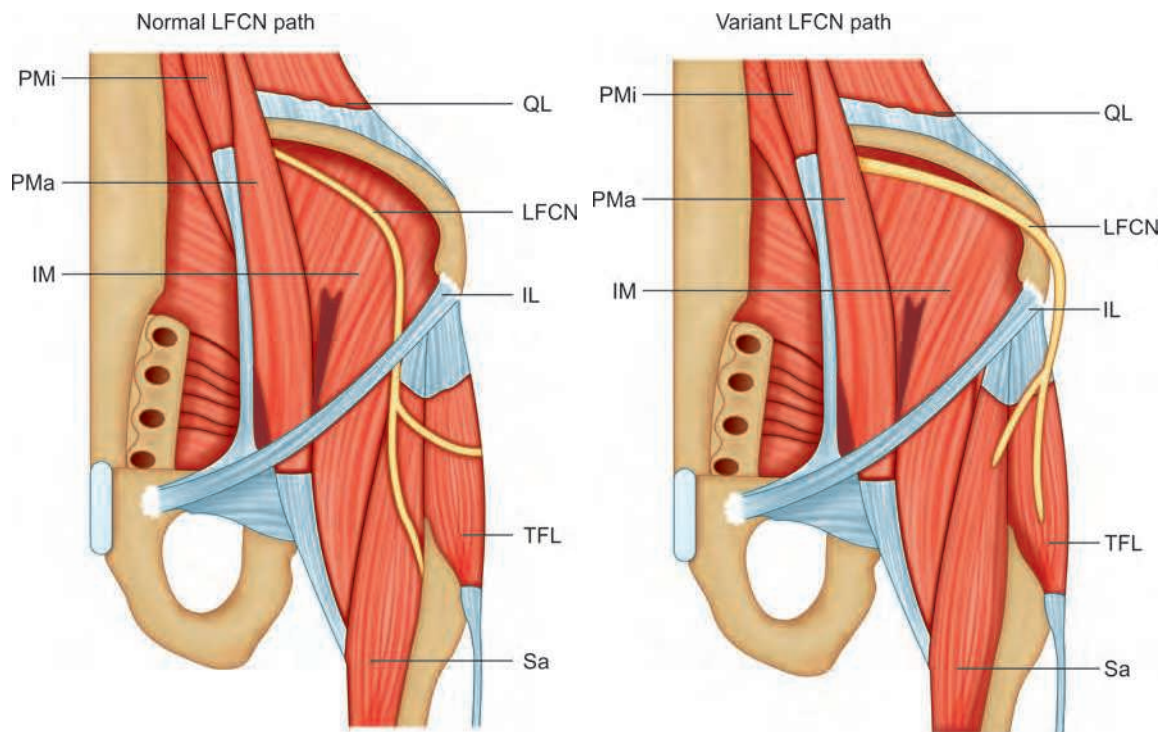


Fig. 31.1: Variant course of the lateral femoral cutaneous nerve (LFCN) which can place it at risk during anterior iliac crest bone graft harvest. (IL: Inguinal ligament; IM: Iliacus muscle; TFL: Tensor fascia lata; Sa: Sartorius; PMa: Psoas major; PMi: Psoas minor).

commonly affected viscera; however, involvement with other organs has been reported.⁵⁷ Risk factors for herniation include larger tricortical graft harvest and more aggressive dissection and retraction of the inner table components. Repair of these defects is often uncomplicated, although the use of mesh implants may be necessary to close the defect.

The ilium is notable for its rich intracortical blood supply, which is thought to increase the risk of hematoma formation after iliac crest harvesting. Standard preventative measures, such as the application of bone wax or coagulative gel foam, as well as vacuum-assisted wound drainage, decrease the risk of hematoma and are recommended in all cases of bone graft harvest.

Intramedullary

Many of the potential complications of intramedullary bone graft harvesting are similar to that reported for intramedullary nail placement. A case of a femoral neck stress riser has been reported as occurring secondary to an aggressive, large-diameter entry through the piriformis fossa;¹⁴ however, the other current studies on this technique reported no other major complications necessitating return to the operating room.⁵⁸⁻⁶¹ There have been reported cases of

thinning of the anterior cortex due to eccentric reaming with the cutting head, and even perforation through the anterior cortex.⁵⁸ However, these were treated nonoperatively with temporary partial weight bearing restriction, and did not necessitate a return to the operating room. This complication may be avoided by frequent fluoroscopic checks during reaming, paying especially close attention to the lateral view in order to evaluate the anterior cortex. More data with longer term follow-up are needed to determine the true incidence of eccentric reaming into the anterior cortex, and if there is associated morbidity, such as a predisposition for femoral shaft fractures.

KEY POINTS

- Graft harvested from the iliac crest remains the gold standard for autogenic bone graft, and demonstrates superior osteogenic, osteoinductive, and osteoconductive properties to allograft.
- Intramedullary bone marrow harvest with the femoral shaft reamer-irrigator-aspirator represents a potential new source of cancellous bone graft while avoiding many of the complications frequently associated with iliac crest bone graft.

- During anterior iliac crest harvest, the 2 cm of crest proximal to the anterior superior iliac spine should be spared in order to avoid injury to the lateral femoral cutaneous nerve, as well as to decrease the risk of ASIS avulsion fracture.
- Care should be taken to maintain control of the osteotome during iliac crest harvest, as violating the sciatic notch or the inner and outer tables of the pelvis can result in disastrous neurovascular compromise.
- The risk of chronic donor site pain from the iliac crest may be decreased by the use of local anesthetic infusions, transversalis fascia plane block, and crest reconstruction.

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This level I study compared the use of local bone grafting to iliac crest bone graft, and showed that local bone graft for single level instrumented posterolateral fusion leads to an identical fusion rate as ICBG, while decreasing surgical time and complications. It should be noted that the only complications that were significantly increased with iliac crest harvest consisted of donor site pain and surrounding area sensory loss. No complications occurring in either group necessitated a return to the operating room.

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This study directly compares the volume and quality of graft obtained from both the iliac crest and intramedullary cavity. It also investigates the technique of harvesting from the intramedullary cavity versus the iliac crest,

comparing the harvest time, blood loss, and postsoperative considerations, such as donor site pain and functional impairment.

- Sagi HC, Young ML, Gerstenfeld L. Qualitative and quantitative differences between bone graft obtained from the medullary canal (with a Reamer/Irrigator/Aspirator) and the iliac crest of the same patient. *J Bone Joint Surg Am* 2012;94(23):2128-35.

This study directly compares the genetic and histologic profiles of graft from intramedullary versus iliac bone in ten consecutive patients. It showed that viable osteocytes and their progenitor cells exist in the reaming debris, and that it also displayed upregulation of genes related to bone repair and formation.

- Delawi D, Dhert WJ, Castelein RM. The incidence of donor site pain after bone graft harvesting from the posterior iliac crest may be overestimated: a study on spine fracture patients. *Spine (Phila Pa 1976)*. 2007;32(17):1865-8.

This study shows that patients with spinal fusion occurring at higher vertebral levels were much less likely to report chronic donor site pain. Because lower back pain may be confused for donor site pain, it is possible that patients fail to differentiate the two when reporting chronic donor site pain in other studies.

- Singh K, Phillips FM, Kuo E. A prospective, randomized, double-blind study of the efficacy of postoperative continuous local anesthetic infusion at the iliac crest bone graft site after posterior spinal arthrodesis: a minimum of 4-year follow-up. *Spine (Phila Pa 1976)*. 2007;32(25):2790-6.

This study demonstrated that a continuous 48 hour infusion of 0.5% marcaine into the iliac crest donor site through a catheter-infusion system had a significant effect of reducing perioperative and chronic donor site pain through a follow-up of 4 years. There were no long term complications associated with the infusion system, which was tolerated well by patients.

Bone Graft Substitutes

John Street

Snapshot

- » Biology of Spinal Fusion
- » Bone Graft Incorporation
- » Three Biological Phases of Spinal Fusion
- » Characteristics of Bone Graft Material Options
- » Currently Available Bone Graft Materials
- » Autologous Graft
- » Allograft
- » Demineralized Bone Matrix
- » Minerals
- » Cements
- » Calcium Sulfate
- » Bioactive Glass
- » Osteopromotive Agents/Growth Factors
- » Cell-Based Therapies

INTRODUCTION

It is estimated that, globally, more than 500,000 bone grafting procedures related to spine fusion are performed annually.¹ Autologous bone graft is often limited in its availability while its harvesting may be associated with significant donor morbidity. Such reality has stimulated a proliferation of research and corporate interest in identifying and characterizing candidate materials for what is considered an almost limitless market in bone graft replacement.

Today, multiple commercially available bone graft extenders (BGEs) and osteobiologics have been developed with the goal of decreasing surgical morbidity while matching or improving surgical fusion rate. Such enthusiasm, however, must be tempered by objective scientific evaluation and independent clinical testing. Currently, bone graft substitutes, depending on their composition and preclinical testing are subjected to varying degrees of regulatory scrutiny. These inconsistencies make direct comparison of materials difficult and so their true effectiveness in patients is often poorly understood prior to their use by spinal surgeons.

In order to choose appropriate bone graft substitute for our patients and ourselves, it is imperative that we as clinicians have an adequate knowledge of the following issues:

1. The biology of spinal fusion.
2. The characteristics of bone graft material options.
3. Currently available bone graft substitutes.
4. The current best evidence for the use of bone graft alternatives in clinical practice

In this chapter, we will explore these issues in detail, in order to gain a better insight into this myriad group of bone graft alternatives.

BIOLOGY OF SPINAL FUSION

Essentials of Bone Formation

A working knowledge of the basic biology of spinal fusion is essential to a better understanding of the attributes and limitations of bone graft alternatives in a clinical context. The physiological process of spinal fusion has many similarities to that of acute fracture healing,²⁻⁴ occurring through a combination of both intramembranous and endochondral ossification. The essential difference between the

Box 32.1: Intramembranous bone formation.

Step 1: An ossification center develops within the connective tissue, whereby local and systemic mesenchymal stem cells cluster together. These develop into osteoblasts, eventually secreting bone matrix, while some later become trapped within that matrix and become osteocytes.

Step 2: Angiogenesis and vasculogenesis result in blood vessel ingrowth of the matrix, delivering the essential oxygen and nutrients for bone formation. When mature, these blood vessels will become trapped within the developing bone.

Step 3: The immature, or spongy, bone is established.

Step 4: Immature bone remodels under the orchestration of the osteoclast, eventually becoming mature or compact bone.

processes is the relative contribution of a “cartilage intermediary” to the formation of bone, a phase characteristic of endochondral bone formation. While both of these processes are involved in skeletogenesis, long bone growth, bone remodeling, fracture healing and spinal fusion, the essential elements are the same for all physiological and pathological processes of the skeleton.⁵⁻⁷

Intramembranous Ossification

There are *four* key steps in the process of *intramembranous ossification* (Box 32.1).

Endochondral Ossification

There are *five* key steps in the process of *endochondral ossification* (Box 32.2).

BONE GRAFT INCORPORATION

The biology of bone graft incorporation involves many factors.⁴ To look at these factors, we will need to examine several types of grafts. Fresh autograft is the transplantation of living bone that can survive and add to the bone volume and eventually the bone strength. When fresh autograft is added to a recipient site, the incorporation of the graft relates to the recipient site cells as well as to the remaining viable cells within the graft itself. The cellular response seems to be different when using a cancellous graft as opposed to using a cortical one. Cancellous autografts as well as fresh cortical autografts begin their incorporation in much the same way.^{8,9}

Blood clot and hematoma provide the initial environment for the new graft. An inflammatory response then prevails and vascular granulation tissue invades the area.

Box 32.2: Endochondral bone formation.

Step 1: A cartilaginous focus develops in the soft tissues, where precursor cells are driven by ambient oxygen tension and biomechanical load to differentiate into chondrocytes. These cartilage cells subsequently differentiate into osteoblasts, secreting a bony collar.

Step 2: The primary ossification center is established and the cartilage within the central portion undergoes direct ossification.

Step 3: Angiogenesis and vasculogenesis result in vascular invasion of the internal cavities of the primary ossification center, with chondrocytes undergoing orchestrated apoptosis while fibroblasts differentiating into osteoblasts. These osteoblasts secrete an immature spongy bone matrix.

Step 4: During the process of skeletogenesis, a secondary ossification center develops in the epiphysis of long bones.

Step 5: The primary ossification center matures and remodels, forming compact bone with some marrow cavity. In long bones, some hyaline cartilage remains to form the articular and epiphyseal cartilages.

By the end of the second week, the response is that of a fibrous granulation tissue, and cellular death occurs within the graft, which has not yet been reached by the vascular response. At this point, the differences of graft incorporation between cortical and cancellous grafts become evident.

In cancellous autografts, the vascular response is much greater than in cortical grafts. The entire cancellous bed may be completely revascularized within approximately 1–2 weeks. The cell population of this environment comprises predominantly osteoblasts. It is not known if these cells are produced from the recipient site or if they are the descendants of cells transplanted with the graft itself. In any case, these cells line the scaffold presented by the trabeculae of the graft and deposit a seam of osteoid that surrounds and entraps the original dead bone. This entrapped dead bone is eventually resorbed by osteoclasts. Radiographically, the cancellous bone first becomes more dense as the new bone forms on the old trabeculae and then becomes less dense as the osteoclastic remodeling takes place. It would appear that the cancellous graft is completely remodeled and replaced by new bone.^{10,11}

In the cortical autograft, the main differences revolve around the amount of revascularization and the completeness of the remodeling. The cortical bone may not be revascularized as quickly as the cancellous graft. Revascularization takes about 2 months and is caused by the structure of the cortical graft, which does not allow as large

a contact area for vascular penetration between the graft and the host. Revascularization is accomplished through the old haversian and Volkmann canals. Following the revascularity of the periphery of the graft, the interior follows suit quickly. Interior revascularization of a cortical bone graft will start the process of creeping substitution, which first resorbs bone stock before replacement with new viable bone stock. The resorptive phase is seen to be increased over normal levels at 2 weeks, steadily increasing for the next 4 weeks, and then diminishing toward normal by 1 year. The histologic evaluation of this data showed that the resorption process progressed so that the peripheral haversian systems and their adjacent interstitial lamellae were remodeled first and then the interior haversian systems were remodeled without their corresponding interstitial lamellae, thereby leaving areas of dead cortical bone mixed in with the newly remodeled bone. The overall results showed that the bone at the ends of the graft was more completely remodeled than the bone in the center of the graft. The completeness and rate of repair seemed to be related to the remodeling activity, with greater repair associated with more active remodeling. The relationship of this remodeling rate to weight-bearing stresses is unclear.¹¹⁻¹³

The incorporation of cortical allografts differs slightly from that of cortical autografts. In general, the revascularization is much slower and the bone formation is less extensive. Resorption may play a much larger part in the graft incorporation. The temporal sequence of the cortical bone allograft shows an inflammatory response for several weeks. The major cell type at this time is the lymphocyte. The inflammatory response lasts for another month or two, during which time a fibrous *encapsulation* of the allograft takes place. Gradually, the graft may be incorporated into the host tissue. The time period associated with the incorporation of the allograft is one indication of the acceptance or rejection of the graft. Callus formation is a good sign but may not be present to any great extent if rigid internal fixation is used.

■ THREE BIOLOGICAL PHASES OF SPINAL FUSION

Boden, using a rabbit model, was the first to describe in detail the three distinct phases (*the inflammatory phase*, *the reparative phase* and *the remodeling phase*) of the spinal fusion process.^{14,15}

Inflammatory Phase

The *inflammatory phase*, which lasts up to 14–28 days in humans, begins with surgical exposure and bone decortication, leading to hematoma formation and a local accumulation of myriad cytokines including tumor necrosis factor α , basic fibroblast growth factor, vascular endothelial growth factor (VEGF), placental like growth factor and bone morphogenetic proteins (BMPs). Rapid and profuse vascular ingrowth characterizes this inflammatory phase. Intramembranous bone formation occurs immediately adjacent to the site of decortication and is known as the *outer zone* of fusion. Endochondral bone formation predominates between these sites, e.g. *intertransverse* area and is known as the *central zone*.

Reparative Phase

The reparative phase is characterized by further vascularization of the fusion bed, and an orchestrated resorption of necrotic tissue. The pluripotent mesenchymal cells that have migrated from the local soft tissues and via the neovascularization then differentiate into chondroblasts and osteoblasts. The earliest evidence of fusion is seen with ossification of the preliminary cartilaginous tissue into immature spongy bone. Fifty percent of fusion is thought to have occurred by the conclusion of this reparative phase, approximately 42–84 days following decortication.

Remodeling Phase

The *remodeling phase* is characterized by the transformation of immature woven bone into mature lamellar bone with cortical and cancellous components. This has largely occurred by 180 days postdecortication, although fusion mass remodeling continues to occur for life. The anatomical and physiological characteristics of this fusion mass continue to evolve, with the exact nature at any time being determined by the ambient biomechanical and biological environment.

■ CHARACTERISTICS OF BONE GRAFT MATERIAL OPTIONS

When considering the appropriate bone graft substitute, graft extender or osteobiologic for a particular clinical scenario, we must examine the available options cognizant of the biological and structural characteristics shown in Box 32.3.

Box 32.3: Characteristics of bone graft materials.

Osteogenesis
 Osteoinduction
 Osteoconduction
 Osteopromotion
 Structural integrity
 Osteointegrative ability/bioactivity

Osteogenesis

Osteogenic grafts contain a cellular population, with the necessary synthetic machinery, osteoblasts, and/or progenitor cells, which are capable of surviving the transplantation process and can thus independently produce new bone in the transplanted site. Autologous bone graft is the only truly osteogenic graft alternative. Iliac crest (IC) harvested autograft has more osteogenic potential than local bone graft (LBG) from laminectomy/facetectomy.

Osteoinduction

Osteoinductive graft materials contain a profile of cytokines and growth proteins that are necessary to induce the differentiation of progenitor cells into bone-producing cells (osteoblasts). This is a complex process involving the mediation of multiple signaling factors including the transforming growth factor β (TGF- β) superfamily of BMPs. Through this process, a true osteoinductive agent can stimulate bone production anywhere in the body, including nonbony locations. A material is defined as osteoinductive if it is shown to induce ectopic bone formation in athymic nude mice. However, we must be very careful not to equate this property with inherent osteoinductive ability in a clinical setting. Many calcium phosphate bone substitutes have been marketed as osteoinductive on the basis of this model. However, the “osteoinductive” properties of these materials are actually related to their architectural features of geometry, topography, and porosity, which allow attachment of circulating and locally produced BMPs. This concentration of BMPs over time will induce bone formation independent of the calcium phosphate bone graft substitute. Hence, in reality we are observing delayed osteoinduction by BMPs naturally occurring in the body.

Osteoconduction

Osteoconductive grafts provide a bioactive three-dimensional matrix structure, similar to cancellous bone, which

allows for and stimulates bony ingrowth and ongrowth. This matrix supports and facilitates fibrovascular ingrowth, hosts progenitor cell migration into the scaffold, osteoblast attachment and eventual manufacture of new bone. This passive ability depends on direct contact with exposed bony surfaces. Allograft materials and demineralized bone matrix (DBM) are primarily osteoconductive. Demineralized bone matrices may also have weak, inconsistent osteoinductive capacity.

Osteopromotion

Osteopromotive agents enhance de novo bone healing that is already taking place, while these agents may not have any inherent osteogenic, osteoinductive or osteoconductive capabilities. Osteopromotive agents include platelet-derived growth factor (PDGF), TGF β -1, insulin-like growth factor 1 and VEGF, all of which have been shown to have osteopromotive potential in preclinical studies. Platelet-rich plasma (PRP), which contains a concentration of these agents, can be easily derived from whole blood samples using any of a number of commercially available isolation systems.

Structural Integrity

In some clinical situations, e.g. interbody grafting after discectomy or vertebrectomy, a graft material with immediate inherent structural integrity may be required. The clinically relevant material properties of this graft material will include compressive strength, and resistance to torsion and shear. If this structural graft material must be fixed in place, e.g. with a threaded screw, then it should not be *brittle*. A material is brittle, if when subjected to stress, it breaks without significant deformation (strain). Brittle materials absorb relatively little energy prior to fracture, even those of high strength. The processing of many structural allografts renders them brittle.

Osteointegrative Ability/Bioactivity

This is the capability of the graft material to integrate and bond to the host bone through an interaction between the biomaterial and the surrounding tissue. In bone graft substitutes, bioactivity describes the influence of a material on bone formation. By changing surface properties of the graft material, e.g. calcium phosphate ceramics, bone integration and bonding can be influenced. From a cellular

perspective, bioactivity reflects the attachment and differentiation of local native osteogenic cells on the surface of the graft material.

CURRENTLY AVAILABLE BONE GRAFT MATERIALS

To address donor site morbidity, volume availability, potential immunogenicity, and disease transmission, a variety of bone graft substitutes have been developed. No perfect substitute yet exists that embodies all the ideal qualities of autograft (osteogenic, osteoconductive, osteoinductive, structural integrity, bioactivity). Except for BMPs, which are discussed in another chapter in this book, these products do not routinely have osteogenic or osteoinductive capabilities unless mixed with autograft or bone marrow aspirate (BMA). Most of these agents have osteoconductive capabilities, creating a matrix for host cells to regenerate bone. They can also be osteointegrated, reflecting their bioactivity. Bioabsorbability and strength profile should be similar to cortical or cancellous bone, but this remains variable among the different products. Cost is also highly varied. The following is a list of the current most commonly utilized bone graft material types. This list is not designed to be exhaustive of all available products, but rather classifies the products into materially distinct types.

1. *Autologous graft*: structural or nonstructural, local or iliac crest harvested, vascularized or non, BMA
2. *Allograft*: structural or nonstructural
3. DBM
4. Minerals
 - a. Hydroxyapatite (HA)
 - b. Coralline HA
 - c. Ceramics
 - d. Composites
5. Cements
6. Calcium sulfate
7. Bioactive glass (BAG)
8. Osteopromotive agents/autogenous growth factors
9. Cell-based therapies

Requirements for an ideal bone graft substitute are as listed in Box 32.4.

A summary of the advantages and disadvantages of the various graft materials is given in Table 32.1. Techniques and complications of bone graft harvesting, vascularized grafts and BMPs will not be examined in detail in this chapter, as they are the focus of other chapters in this textbook.

Box 32.4: Properties of the ideal bone graft substitute.

- Biocompatibility
- Osteoinduction
- Osteoconduction
- Osteopromotion
- Porosity
- Stability under stress
- Resorbability/degradability
- Plasticity
- Sterility
- Stable and long-term integration of implants

AUTOLOGOUS GRAFT

Iliac Crest Bone Graft and Local Bone

The gold standard substance that provides all of the necessary factors for bone formation (osteogenic, osteoconductive, osteoinductive, structural integrity, bioactivity) is autogenous bone (AB) graft. In 1911, Hibbs¹⁶ described the use of LBG in the first spinal arthrodesis performed in the setting of tuberculosis of the spine. Autograft is the preferred bone graft material because of its availability, inherent fusion-developing properties, low cost compared with commercially available grafting substitutes, and the absence of concerns regarding possible disease transmission or tissue incompatibility. The iliac crest, with its potential source of cortical and cancellous bone graft, is the current go to site for *distant site autograft*. These grafts are the benchmark to which allograft and substitutes are compared for in vivo performance.¹⁷⁻²¹

Unfortunately, morbidity associated with its use is also well reported. Donor site morbidity can be attributed to the harvesting procedure of the iliac crest bone graft (ICBG). This procedure is associated with longer operative times, increased estimated blood loss, and a longer hospital stay. Pain is the most common complication, but hematomas, paresthesias, and wound complications can also occur. Some authors have reported chronic pain at the graft site in up to 60% of patients.^{22,23}

In the very cases where large amounts of high-quality cancellous bone graft material is required, e.g. revision long thoracolumbar fusion for deformity in the elderly, there is often less ICBG available for harvest, and the quality of this bone (osteogenic, osteoconductive, osteoinductive,

Table 32.1: Advantages and disadvantages of most common bone grafting options.

<i>Graft material</i>	<i>Advantages</i>	<i>Disadvantages</i>
<i>Autograft</i>		
Iliac crest	Gold standard Large availability, low cost Osteoconductive Osteoinductive Osteogenic	Donor site morbidity Increased blood loss Increased operative time
Local bone	Low cost, minimal morbidity Osteoconductive Osteoinductive Osteogenic	Limited availability Biologically inferior to iliac crest bone graft
<i>Allograft</i>		
Fresh frozen	Large availability, low cost Osteoconductive	Disease transmission Inflammation No osteoinductive or osteogenic capacity
Freeze-dried	Large availability, low cost Osteoconductive	No osteoinductive or osteogenic capacity
Demineralized Bone matrix	Large availability, low cost Osteoconductive	No osteogenic capacity Inconsistent limited osteoinductive capacity
Ceramics	Large availability Immediate structural integrity No immunogenicity	No organic matrix No osteoinductive or osteogenic capacity
β-Tricalcium phosphate	Three-dimensional structure of bone Porous	Brittle Limited compressive strength
Coralline HA	Immediate structural integrity	Slow in vivo resorption
Silicate-substituted calcium phosphate	Immediate structural integrity	Costly No osteoinductive or osteogenic capacity
Calcium sulfate	Quick in vivo resorption Biocompatibility	Quick in vivo resorption Wound drainage
Autologous growth factors	Osteoinductive	Cost Questionable safety/dosing Variable efficacy
Bone marrow aspirate/MSCs	Osteoinductive	Osteoinductive only Needs carrier Questionable efficacy

(HA: Hydroxyapatite; MSCs: Mesenchymal stromal cells).

bioactivity) is poor. These concerns have led to the increasing body of research focused toward developing an ideal bone graft substitute.

Other more recent studies question whether iliac crest donor site pain may be overestimated. Delawi et al.²⁴ found that the incidence of donor site pain was <15% in patients with a more proximal level of fusion compared to 40% in those with a lower level of fusion, suggesting that donor site pain may be related to the lumbar procedure itself and not so much the donor site. Another recent study of 112 patients treated with posterolateral fusion (PLF) with

or without bone graft reported that the incidence of tenderness over either posterior iliac crest was up to 50% in patients who did not undergo crest harvesting. The incidence of concordant pain from the crest where the graft was harvested was only 19%. These studies, therefore, question the assertion that bone graft harvesting is indeed a significantly morbid procedure.²⁵

While autograft is considered the “gold standard” for spinal fusion, it is interesting that it has never been directly compared with no bone graft material, in the clinical setting. Similarly, published fusion rates with autograft

vary with marked differences reported based on fusion location, graft harvest location, surgical technique, use of instrumentation, volume of graft used, preparation of fusion base, and the method used to assess whether bony fusion has been achieved.²⁶⁻²⁸

Transplanted cancellous bone graft may have few osteoblasts, but it does contain precursors that maintain their osteogenic potential and, therefore, their ability to form new bone. The local graft environment also affords an enriched osteoinductive environment and one that is osteoconductive, but has less initial structural strength. Structural or cortical grafts, however, can assist in maintaining structural support while providing osteoconduction and some osteoinduction. Cortical graft, as typically utilized in the intervertebral space or following vertebrectomy, provides strong structural support within the first 6 weeks after transfer, but they are prone to fracture (brittle) and the processes of osteointegration, resorption and remodeling take many months, to years.

Posterior spinal arthrodesis, typically when combined with neural decompression, can provide a large amount of *local autograft bone*, harvested from the laminectomy and facetectomies. Anterior vertebrectomy, usually in the setting of trauma or deformity, also provides a large amount of local autograft bone. Local bone graft harvesting does not require separate exposure and avoids many of the complications associated with iliac crest graft harvesting. Disadvantages of local bone include its relatively limited quantity, particularly in the setting of revision surgery with prior laminectomy, and its greater composition of cortical bone compared to cancellous bone.

While intuitively there is concern regarding poor fusion rates associated with its use, several studies have reported fusion rates that are comparable to those achieved by ICBG, particularly for single-level fusions. In a retrospective comparative study of 76 patients treated with instrumented PLF, Sengupta et al.²⁹ report overall fusion rates of 75% with ICBG and 65% with local bone. However, when only multilevel fusions were included in the analysis, the difference was significantly greater with fusion rates of 66% for ICBG and only 20% for LBG. Despite decreased rates of fusion, no significant difference in overall clinical outcome is noted between these two groups, absent those patients ultimately requiring a revision for pseudarthrosis.

Ohtori et al.³⁰ prospectively examined single-level instrumented PLF at L4-L5 with a LBG versus an ICBG for degenerative spondylolisthesis. Eighty-two patients were randomized into a local autograft group ($n = 42$) and

an ICBG group ($n = 40$). Rate and time to fusion were equivalent (90% fusion at 8.5 months in the LBG group, and 85% fusion at 7.7 months in the ICBG group). Schizas and coworkers prospectively reviewed 59 patients undergoing instrumented PLF and at 12 months found equivalent fusion rates (76% local vs. 68% ICBG).

Despite the use of rigid instrumentation, the rate of pseudarthrosis is not insignificant with iliac crest autograft. Dimar recently published a retrospective review of 194 patients with degenerative lumbar disease who underwent single-level, instrumented lumbar fusion with iliac crest autograft. Evidence of bridging bone was assessed using plain radiographs and fine-cut computed tomographic (CT) scan with CT reconstructions. At 2-year follow-up, 84% of the patients had evidence of fusion defined as the presence of bridging bone on CT scan.²⁵

Autologous bone from alternate sites is also available for grafting. Sawin et al.³¹ found successful fusion in 296 of 300 posterior cervical cases (98.6%) using rib autograft, whereas iliac crest successfully fused 49 of 52 cases (94%). Donor site morbidity and other major complications were significantly less common in the rib autograft group compared with the iliac crest group. No study has directly compared the use of rib with ICBG in lumbar spine procedures, probably because lumbar procedures do not readily expose the ribs as they would for the thoracic spine.

Bone Marrow Aspirate

Bone marrow aspirate is an alternative autologous graft material with inherent osteogenic and osteoinductive capabilities. It may be obtained readily from the anterior or posterior iliac crest by open or percutaneous routes. There are multiple commercially available bone marrow aspiration sets available. Bone marrow aspirate is highly cellular, containing large populations of stem cells with osteogenic capability. The aspirate also contains concentrated volumes of osteoinductive growth factors. Bone marrow aspirate, however, is neither an osteoconductive nor a structurally capable material and so is typically used in conjunction with products that are osteoconductive and/or structurally capable, such as autograft, allograft, DBM or other extenders. A comparison of bone marrow obtained from both the iliac crest and vertebral body through posterior aspiration of 21 patients by McLain et al.³² found that the vertebral body had a much higher concentration of bone progenitors than iliac crest, making it a more useful site for aspiration.

Neen et al.³³ examined BMA combined with a type 1 collagen/HA matrix (Healos) as an alternative to ICBG in a prospective case-controlled study of both posterolateral and interbody fusion. For posterolateral lumbar fusions, there were equivalent radiologic fusion rates for the two groups with no significant difference in the subjective and objective clinical outcomes. The radiologic fusion rate was significantly lower when Healos had been used for lumbar interbody fusions. Clinical outcomes for both groups were similar. There were no lasting complications associated with Healos use compared with a 14% persisting donor site complication rate in the autograft patients.

In a systematic review of cell-based therapies for spinal fusion, Khashan et al.³⁴ concluded that the available evidence, as of 2012, was insufficient to support the use of mesenchymal stromal cells (MSCs) or BMA combined with synthetic or allograft materials as a substitute or supplementary graft to autologous bone graft. This systematic review of the literature posed the following clinically relevant key questions (KQs):

1. Does the use of MSCs or BMA combined with synthetic or allograft extenders contribute to thoracolumbar fusion rates that are comparable to the rates achieved by the use of iliac crest graft?
2. Are these fusion rates comparable to those of LBG?
3. Is the addition of stem cells (SC) or BMA to ICBG or LBG contributes to better thoracolumbar fusion rates?
4. Are the cervical spine fusion outcomes achieved by the use of stem cell matrix (SCM) or BMA with synthetic or allograft scaffolds comparable to the ICBG or LBG outcomes?
5. Was there any difference in terms of fusion rates, when MSCs were used as compared to BMA?

For KQ1, four level II and III studies used ICBG as control. The results of these studies were inconsistent, and the overall body of evidence was found insufficient. Three level II and III studies were identified for KQ2. Comparable fusion rates were demonstrated between LBG and BMA combined with calcium phosphate or collagen carrier. The overall body of evidence was found weak. For KQ3, one level III study was found. No significant difference was found in the fusion rates. No studies met the criteria for KQs 4 and 5.

■ ALLOGRAFT

Cadaveric allograft is a common choice for use for interbody fusions in the cervical and lumbar spine, but it is

limited in terms of the ideal bone graft characteristics. The architecture of allograft creates a natural osteoconductive scaffold. Allograft also demonstrates good osteointegrative capabilities at the host-recipient interface. By nature of allograft processing, osteogenic cells are largely unavailable. Osteoinductive properties fluctuate depending on the preparation method, but are generally inconsistent and poor.

Allografts are available as fresh, frozen or freeze-dried preparations. Fresh allografts are not routinely used because they may be quite immunogenic and are at greater risk of disease transmission. Frozen allografts are primarily prepared by freezing, whereas freeze-dried allografts are prepared by freezing, and then dehydrating to approximately 25% of water. Further processing is performed with either ethylene oxide or gamma irradiation to make allografts safer with regard to immunogenicity and disease transference. This processing, however, reduces the osteoinductive capabilities, structural strength, and osteointegrative ability to varying degrees. Gamma irradiation tends to affect mechanical integrity more, whereas ethylene oxide affects the osteoinductive capabilities. Frozen allografts are more immunogenic and have a shorter shelf-life than freeze-dried, but freeze-dried allografts have less structural strength and less osteoconductive capabilities.^{35,36}

Allograft is available as cortical, cancellous or corticocancellous graft. Forms include powder, chips, wedges, pegs, dowels, or struts. Allograft can be machined and custom shaped if necessary. Cancellous graft is traditionally incorporated by endochondral ossification through the allograft scaffold with minimal initial strength that increases over time. In contrast, incorporation of cortical graft is by creeping substitution by way of intermembranous ossification within initial inherent structural strength, which weakens with resorption, eventually strengthening with bone deposition and organization.⁸

Complications with allograft use include graft fracture, lack of integration with surrounding peripheral bone, and infection. Transference of viral parts is also a potential concern. Reported rates of disease transmission are one in 1.6 million with fresh frozen and one in 2.8 billion with freeze-dried allograft. In spine surgery, there is only one reported case of HIV transmission.²⁷

In a prospective cohort study of 20 patients undergoing instrumented PLF, ICBG, frozen allograft, freeze-dried allograft, and a mixture of allograft and autograft were compared. There was a 0% fusion rate for freeze-dried allograft alone, and an 80% fusion rate with ICBG at 24 months.

Fresh frozen allograft has also been compared to ICBG for posterolateral instrumented lumbar fusion in 69 patients, with clinical outcomes being equivalent at 6 years. Radiological fusion rate was not reported in this study.³⁷

The efficacy of freeze-dried allograft in adolescent idiopathic scoliosis (AIS) fusion has been shown. Knapp et al.³⁸ retrospectively reviewed 111 patients at 5 years, with a combination of freeze-dried allograft chips and local autograft consistently achieving a 97% fusion rate. Jones et al.³⁹ also reported fusion rates of 93% in 55 patients with use of freeze-dried allograft chips and local autograft at 3-year follow-up.

Allograft is also used as a structural interbody graft in the cervical and lumbar spine. Both fresh frozen and freeze-dried forms are used. Miller et al.⁴⁰ reported a systematic review of safety and effectiveness of bone allografts in anterior cervical discectomy and fusion (ACDF) surgery. The primary aim of this review was to evaluate clinical and radiographic outcomes in studies of ACDF using allograft versus ACDF with autograft, ACDF with cage devices and cervical disc arthroplasty for the treatment of symptomatic cervical disc disease. After applying strict inclusion criteria, 21 comparisons from 20 studies formed the basis for this review. Patient outcomes included neck and arm pain, neck disability index, physical component summary and mental component summary scores from the Short Form 36 (SF-36), radiographic fusion rate and select adverse events (e.g. wound infection, dysphagia, and adjacent segment degeneration). The four treatment groups included ACDF with allograft (allograft, $n = 1341$), ACDF with autograft (autograft, $n = 568$), ACDF with cage (cage, $n = 87$), and cervical disc arthroplasty (arthroplasty, $n = 603$). Neck pain was reduced similarly by 63–69% in all groups. Comparable improvements were realized in arm pain after ACDF with allograft (75%) or arthroplasty (73%) that were greater than other treatment groups (62–68%). There was notable improvement in neck disability (61–65%) with allograft and arthroplasty after treatment. Physical component summary scores improved with allograft (42%) and arthroplasty (44%). Mental component summary scores improved modestly (16–21%) with allograft and arthroplasty. Fusion rates were 91% for allograft and autograft and 97% for cage. Adverse events were uncommon in all groups.

Given the nature of allograft and its preparation, many have expressed concerns about the biological robustness of this graft alternative in patients who smoke. Luszczek et al.⁴¹ examined the effect of smoking on the success of

single-level ACDF using allograft and a rigid plate. This study is composed of patients from the control groups of five separate studies evaluating the use of an anterior cervical disc replacement to treat cervical radiculopathy. For each of the five studies, the control group consisted of patients who underwent a single-level ACDF with allograft and a locked cervical plate. The authors reviewed data of 573 patients; 156 patients were smokers and 417 were nonsmokers. A minimum follow-up period of 24 months was required for inclusion in this study. Fusion status was assessed by independent observers using lateral, neutral, and flexion/extension radiographs. An overall fusion rate of 91.4% was achieved in all 573 patients. A solid fusion was shown in 382 patients (91.6%) who were nonsmokers. Among patients who were smokers, 142 (91.0%) had radiographic evidence of a solid fusion.

Thalgott et al.⁴² compared fresh frozen and freeze-dried allograft used as a structural interbody graft in 50 patients undergoing circumferential lumbar fusion. At 24 months, there was a greater fusion rate seen with fresh frozen allografts (65% freeze-dried vs. 77% fresh frozen). Overall clinical outcomes were equivalent between graft options.

In a prospective randomized study, Putzier et al.⁴³ compared ICBG with freeze-dried allograft chips for single-level posterior instrumented lumbar interbody fusion. The radiological outcome was based on both fusion rate (radiographs, computed tomography) and the bone mineral density of the grafts. After 6 months, the X-rays of the patients with allograft showed significantly lower rates of fusion. After 12 months, radiological results showed a similar fusion rate in both groups.

In a prospective study of 144 patients undergoing PLF, Jorgenson et al.⁴⁴ compared ICBG alone, ICBG mixed with ethylene oxide-treated allograft and ethylene oxide-treated allograft alone. Patients served as their own controls by placing ICBG on one side of the spine and the composite on the other side. The authors found that ICBG was significantly superior at producing fusion radiographically compared with allograft alone and allograft mixed with ICBG.

■ DEMINERALIZED BONE MATRIX

Demineralized bone matrix is the allograft that has been crushed to a consistent particle size and decalcified. Subsequent processing reduces immunogenicity and the risk of disease transmission. The product maintains the osteoconductive feature of the original allograft through the

organized trabecular collagenous structure of type I collagen and noncollagenous proteins. Removal of the mineral from the allograft improves the potential, albeit variable osteoinductive capability.

The collagenous framework allows for new vessel ingrowth, the infiltration of mesenchymal and precursor cells and eventual bone formation. The osteoinductive growth proteins available in the extracellular matrix induce mesenchymal cells to differentiate into bone-producing cells, but this ability is variable depending on storage, processing and the inherent capability of the donor tissue. In practical terms, the apparent osteoinductive capacity of these materials is more related to the concentration of locally produced native growth factors in the collagenous framework. Demineralized bone matrix does not impart structural integrity, but is useful as a space filler and as a composite with other graft materials, such as harvested autograft, bone marrow, minerals and calcium sulfate.⁴⁵

Demineralized bone matrix is manufactured with various carrier vehicles, such as glycerol, starch, collagen and hyaluronic acid. Different forms include moldable paste, putty, strips, gel, freeze-dried powder and granules. The primary negatives of DBM are the inherently variable osteoinductive properties, the lack of structural integrity, carrier concerns, such as glycerol (The glycerol carrier has been implicated as the nephrotoxic agent in a rat model using Grafton DBM. Bostrom et al. implanted rats with very high doses of and on autopsy found that the rats had died from hemorrhagic nephrotoxicity) and possible disease transmission compared with standard autograft.⁴⁶ Osteoinductive capacity is relatively low, and the variability is found, not only between the different manufacturing companies but also in products from the same manufacturer.

Wang showed that commercially available DBMs have highly variable osteoinductive potentials in a rat model. Comparing Osteofil, Grafton, Dynagraft and ICBG, fusions were assessed at 2, 4, 6 and 8 weeks postoperative with plain radiographs, manual palpation and histology after a PLF. Osteofil and Grafton showed significantly higher rates of fusion at all time points compared to Dynagraft and ICBG.^{47,48}

Bae et al.⁴⁸ quantified concentrations of BMP-2 and BMP-7 in a single DBM product and found significant lot-to-lot variability, not only in BMP concentrations but also in *in vivo* rates of fusion in a rat model. Fusion rates correlated positively with BMP-2 and BMP-7 concentra-

tions in a dose-dependent manner. They also found that the concentrations of BMP-2 and BMP-7 were one million times less than concentrations required for fusion clinically.

In a multicenter prospective study of 120 patients undergoing posterolateral spine fusion, Grafton gel-DBM combined with autologous ICBG was compared to autologous ICBG alone.⁴⁹ The composite graft was placed on one side and ICBG alone was placed on the contralateral side. Fusion rates were similar in the composite group (52%) and autologous graft alone groups (54%). You will have noticed that these reported fusion rates are relatively low compared to the rest of the literature, likely a result of very strict radiographic criteria for fusion.

Vaccaro et al.⁵⁰ studied 73 patients undergoing posterolateral instrumented lumbar fusion and reported that a composite of DBM Grafton Putty and BMA produced fusion rates similar to ICBG alone (63% Grafton Putty and BMA vs. 67% ICBG). Cammisa et al.⁵¹ prospectively compared DBM Grafton and ICBG to ICBG alone in 120 patients undergoing instrumented PLF. At 24 months, fusion results were equivalent (52% vs. 54%), although the study had a 30% rate of lost to follow-up.

In a retrospective study by Vaidya et al.⁵², DBM with allograft spacers demonstrated comparable fusion rates, cervical Oswestry scores, Visual Analogue Scale (VAS) for arm pain and neck pain, and radiographs as compared with recombinant human BMP 2 (rhBMP-2) and PEEK cages in 46 patients who underwent instrumented ACDF. Demineralized bone matrix and allograft spacers seem to be a safe and effective graft alternative to rhBMP-2 and PEEK cages for ACDF surgery, due to fewer side effects, cheaper cost and comparable fusion rates.

Aghdasi et al.⁵³ performed a systematic review of the English-language literature examining the efficacy of DBM in spinal surgery. Only original research articles in peer-reviewed journals that investigated fusion outcomes were included. Scientific validity of articles was appraised using the PRISMA methodology. Study design, DBM type, outcomes and results were reported. Primary outcome of interest was fusion rate. Secondary outcomes included Oswestry Disability Index (ODI), SF-36 survey and pseudarthrosis and surgical failure rates. They identified few prospective randomized controlled trials comparing DBM to autologous ICBG in spine fusion. The highest level of evidence studies have been performed using DBM in posterolateral lumbar fusion and suggest that DBM can be used successfully as a graft extender. In these studies, DBM

has been successfully combined with iliac crest autograft, local bone autograft and bone marrow to facilitate fusion. Grafton, which is a DBM product with a glycerol carrier, has been the most extensively studied DBM to date and success in prospective clinical studies has been observed with gel, putty and matrix formulations. Several case series support the use of DBM in the cervical spine although prospective controlled trials are lacking. They concluded that although the literature appears to support the use of certain DBM formulations in spine fusion surgery, further randomized controlled trials are necessary to fully understand the potential of different DBM products and the appropriate clinical scenarios for their use.

MINERALS

Hydroxyapatite

Hydroxyapatite is a crystalline structure and the basic component of the mineral state of bone. Its composition differs between the different mineral precursors, calcium phosphate and tricalcium phosphate. These compounds have a three-dimensional framework similar to bone and so have osteoconductive and osteointegrative capability. Although such agents may have initial structural integrity, they are eventually remodeled and replaced by immature and finally mature woven bone. Because of the absence of cellular or growth factor components, they lack any inherent osteoinductive or osteogenic capacity. They have different fabrication techniques, crystallinity, pore dimensions, mechanical properties and resorption rates. They are clinically attractive bone graft alternatives because of being non-immunogenic, unlimited in supply, easily sterilized and readily stored. Disadvantages include their brittle structure and low tensile strength.^{35,54}

Similar to the three-dimensional framework of bone, these highly porous compounds act as scaffolds allowing fibrovascular ingrowth, inward migration of bone-producing cells and spongy or immature bone deposition. Mineralization and remodeling occurs with eventual replacement by mature bone. These agents are available in paste, putties, solid matrices or granular form.

Coralline Hydroxyapatite

Coralline hydroxyapatite (CHA), derived from marine coral, is the sterilized calcium carbonate, which, although highly porous and regular, is very brittle and quick to resorb. Commercially available CHA is processed with

ammonium phosphate and sterilized, thus converting it to crystalline HA.⁵⁵ This product comes in granules or block form and has been combined with autograft, BMA and BMPs.

Lee et al.⁵⁶ reported on a retrospective review of 32 patients undergoing combined posterolateral and posterior lumbar interbody fusion with CHA and local autograft or ICBG alone. They found no differences in the rate of PLF (87% fusion for CHA and local autograft vs. 89% fusion for ICBG).

In a prospective evaluation of 57 patients undergoing PLF, Korolessis et al.⁵⁷ compared ICBG, CHA and BMA. At 12 months, they found that only ICBG had achieved fusion and recommended that CHA not be used alone for PLF in the lumbar spine.

Hsu et al.⁵⁸ reported mixed results with the use of CHA and laminectomy-derived bone as an adjuvant graft material for lumbar PLF. This prospective, case-control study involved 58 patients who underwent lumbar instrumentation-augmented PLF for degenerative spinal stenosis-induced segmental instability. The patients were divided into three groups. Laminectomy bone and anterior iliac crest bone graft (AIBG) were placed in the right intertransverse process space in group 1 (20 patients), CHA and AIBG were placed in group 2 (19 patients) and laminectomy bone and CHA were placed in group 3 (19 patients). Pure autogenous iliac cancellous bone graft was placed in the left intertransverse process space in all the three groups of patients. Successful fusion was determined by two spine surgeons after examining the plain, anteroposterior, bilateral oblique and lateral flexion-extension radiographs. If the examiners did not agree on fusion status, fine-cut CT scans of the fusion mass were used to make the final decision. They found that pure AIBG placed in left intertransverse process space was associated with the best fusion rate. After 6 months, CHA produced a comparable result to laminectomy-derived bone when combined with AIBG. When laminectomy bone was mixed with CHA, the combination failed to yield a satisfactory fusion rate (57.9%) even 1 year after surgery, if no AIBG was added.

The brittleness and poor structural integrity of CHA was demonstrated by McConnell et al.⁵⁹ in a prospective randomized comparison of CHA with autograft in cervical interbody fusion. In this study, 29 patients undergoing anterior cervical fusion and plating were randomized to receive either ProOsteon 200 structural CHA graft or iliac crest tricortical grafts. The SF-36 and ODI were used to measure clinical outcome. Postoperative radiographs

were analyzed for graft fragmentation, loss of height, angular alignment and hardware failure to assess structural integrity of the graft material. Plain radiographs and CT scans were used to evaluate fusion. Both the ProOsteon 200 and iliac crest groups demonstrated significant improvement in clinical outcome scores. There was no significant difference in clinical outcome or fusion rates between the two groups. Graft fragmentation occurred in 89% of the HA grafts and 11% of the autografts ($p = 0.001$). Significant graft settling occurred in 50% of the HA grafts, as compared with 11% of the autografts ($p = 0.009$). One patient in the ProOsteon 200 group required revision surgery for graft failure. The authors concluded that ProOsteon 200 does not possess adequate structural integrity to resist axial loading and maintain disc height or segmental lordosis during cervical interbody fusion.

Ceramics

The synthetic minerals HA and beta-tricalcium phosphate (β -TCP) are calcium phosphate-based ceramics. These ceramics are similar in structure to mineralized bone and so are highly osteoconductive and osteointegrative. Clinically usable ceramics are produced by heating to between 700°C and 1300°C to form the crystallized substance. While this improves compressive strength, the downsides are that it renders the material brittle (poor tensile strength) and very slow to resorb *in vivo*. These compounds are extremely porous, allowing direct fibrovascular invasion and eventual bone deposition. During the resorptive phase of graft incorporation, a portion of the tricalcium phosphate undergoes conversion to HA.^{60,61}

In general, tricalcium phosphate-based products are more porous and resorb at a quicker rate (12–24 months) than HA-based graft options (24–36 months). However, they are also mechanically weaker in compression than HA. There are several commercially available ceramic agents. Both HA and tricalcium phosphate ceramics are available in granules, block, poly or putty forms. Both have compressive strengths similar to cancellous bone and are brittle with poor resistance to shear.^{62,63}

Dai and Jiang,⁶⁴ in a prospective study of 62 patients undergoing PLF with β -TCP and local autograft, found 100% fusion rates on plain radiographic assessment at 3-year follow-up in both groups.

Ransford et al.⁶⁵ reviewed 341 patients undergoing fusion for AIS and noted equivalent fusion rates with less wound healing issues with the β -TCP group compared to the ICBG group.

Linovitz and Peppers⁶⁶ prospectively followed seven patients who underwent either anterior or posterior lumbar interbody fusion. A combination of β -TCP, freeze-dried cancellous allograft and venous blood was used. They reported 100% fusion rates in the 12 levels that were fused.

Silicate-Substituted Calcium Phosphates

Silicate-substituted calcium phosphates have recently gained more attention as an effective bone graft enhancer. Actifuse is composed of 0.8% silica-substituted HA and calcium phosphate. Silicone has been shown in *in vitro* studies to have osteogenic properties. It has a 35–50% porosity, and the silicone allows for a different composition, geometry and surface charge. Jenis and Banco⁶⁷ published a case series of 42 patients undergoing instrumented PLF. Actifuse was combined with BMA obtained from iliac crest, and fusion rates of 35% at 6 months postoperative and 77% at 24 months postoperative were reported.

Nagineni et al.⁶⁸ performed a retrospective analysis of a prospectively collected patient database including 108 patients (204 individual spinal levels). Different surgical procedures performed included 25 ACDFs, 17 posterior cervical fusions, seven combined anterior and posterior cervical fusions, 10 thoracic fusion surgeries, 18 transforaminal lumbar interbody fusions with 12 axial lumbar interbody fusions, 11 transposas discectomy and fusions and eight combined thoracolumbar fusion procedures. Silicate-substituted calcium phosphate was used as bone extender without any additional graft material, BMA or BMP. At a follow-up of 12 (± 4.7) months, 90% of all patients demonstrated radiographical fusion. Fusion rates were highest in the cervical spine (97%) followed by thoracic and lumbar spines (86% and 81%, respectively). There was no radiographical loosening of instrumentation due to infection or nonunion in this series, and no subsequent revisions for nonunion were required.

Composites

These products are often used as expanders for bone autografts combined with bone marrow and as carriers for osteoinductive BMP. There are many composite products available, including those with collagen, HA and tricalcium phosphate, combined with autograft, allograft or BMPs.

Epstein⁶⁹ prospectively evaluated Vitoss (80% tricalcium phosphate and 20% type 1 collagen)/BMA combined with local autograft in performing instrumented one-level ($n = 27$) and two-level ($n = 13$) posterolateral lumbar fusion. By 6 months, 96% of the one-level and 85% of the two-level patients were solidly fused. Epstein⁷⁰ also studied the use of Vitoss/BMA combined with local autograft in noninstrumented one- and two-level posterolateral lumbar in the geriatric population (i.e. average age of 70 years), with a reported fusion rate of 85% at 2-year follow-up.

Yamada et al.⁷¹ developed a hybrid graft (HBG) of porous β -TCP ceramic/percutaneously harvested bone sticks/autologous BMA for lumbar PLF. Sixty-one consecutive patients underwent decompressive laminotomy and one-level instrumented PLF. Each patient in this study had the constructs of the HBG placed on one side of the intertransverse process gutter. An autologous LBG harvested during decompressive laminotomy was placed on the other side as a control. Radiographic evaluation was performed at 6 months, 1 year after surgery and subsequently on an annual basis. The fusion statuses on either side of vertebra were compared. The flexion-extension motion in the dynamic X-rays at the target level decreased over time. Only one case exhibited over 5° of angular motion 2 years after surgery. In the evaluation of fusion status, the fusion rate for the HBG side (68.9% at 6 months, 83.6% at 1 year, 93.5% at 2 years) was higher than that for the LBG side (49.2% at 6 months, 75.4% at 1 year, 89.1% at 2 years) with a significant difference at 6 months after surgery. No significant complications at the donor site were found postoperatively.

CEMENTS

Cements were developed to improve the malleability and moldability of calcium phosphate bone substitute. Calcium phosphate-based cements crystalize to a carbonated HA that maintains a similar structure to the mineral phase of bone.⁷² Because of these unique properties, it may be conveniently injected to fill a bone defect (vertebroplasty) or to augment a screw fixation. Their inner strength lies in their osteoconductive and osteointegrative capabilities, as well as their immediate compressive strength once set. These compounds are available as injectable liquid or moldable putty and set with an isothermic reaction. They resorb by disilusion and osteoclast resorption. Disadvantages include weakness in torsion and shear. One very significant concern is the potential extrusion of cement into

soft tissues or into the spinal canal, thus potentially damaging and creating a neurological deficit. These materials are not routinely used as bone graft substitutes.

CALCIUM SULFATE

Calcium sulfate (CaSO_4 ; plaster of Paris) has been available as a void filler for more than 100 years. It is heated gypsum and when made into powder form has a crystalline microstructure. It is primarily osteoconductive in nature, with better compressive strength than cancellous bone, but poor tensile strength. Primary drawbacks include inconsistency in crystalline structure during setting and rapid resorption by dissolution of the product, which may create an imbalance between bony replacement and resorption.

Calcium sulfate is a completely resorbable, biocompatible BGE. It is quickly resorbed, usually within 6–8 weeks, but has been implicated in causing postoperative wound drainage problems due to an excessive inflammatory reaction.^{73,74} Ziran et al.⁷⁵ reported a 51% wound drainage and 30% infection rate following use of calcium sulfate in treating tibial nonunions. Chen et al.⁷⁶ prospectively reviewed 74 patients who underwent PLF with calcium sulfate and local autograft. At 33-month follow-up, they showed equivalent fusion rates with ICBG (87% calcium sulfate and local autograft vs. 90% ICBG). Niu et al.⁷⁷ had far worse results with the use of calcium sulfate in 43 patients undergoing PLF. At 12-month follow-up, there was a 45% fusion rate with calcium sulfate and BMA compared to ICBG alone.

The breadth of calcium sulfate products has widened to include calcium sulfate mixed with other bone substitute products, DBM and antibiotics (Osteoset).

BIOACTIVE GLASS

Bioactive glass is a solid material composed of sodium oxide, calcium oxide, silicon dioxide and phosphorus. Bioactivity, the interaction between host bone and the graft, depends on the silicon content of the glass. These agents demonstrate strong host graft bonding as the silica breaks down after exposure to host fluid forming a calcific layer from which HA has been laid down. This results in a strong integrated response of the tissue agent interface, creating an enriched osteoconductive environment. Advantages of BAG include its strong and unique bonding capability, osteoconductive properties, ability to modify the composition, possible osteostimulation and good resorption. However, BAG offers little structural support. The product

is available as microspheres, fibers, paste and porous implants. These agents may be injected into a defect or molded into putty.^{78,79}

Acharya et al.⁸⁰ evaluated the efficacy of HA-bioactive glass ceramic composite (Chitra-HABg) as a stand-alone graft substitute in promoting PLF in the lumbar spine as compared with autologous bone. Twenty-four patients underwent instrumented PLF, with Chitra-HABg laid on the left intertransverse bed and autogenous graft on the right side. The primary outcome measure was radiologic consolidation of the graft, and secondary outcome measures were the work status and the modified ODI. Although the study was prematurely terminated owing to the high incidence of resorption of Chitra-HABg, 22 of the 24 subjects were followed up for a minimum of 1 year. At the end of 1 year, excellent radiologic outcome was seen on the right side (autogenous graft) in all the cases, whereas 95% (21/22) of the cases had poor consolidation on the left side (Chitra-HABg). This study clearly demonstrates that Chitra-HABg has no role as stand-alone bone graft substitutes in PLF of the lumbar spine, as the composite undergoes resorption without the formation of bridging callus.

Rantakokko et al.⁸¹ performed a prospective long-term follow-up study of BAG-S53P4 and AB used as bone graft substitutes for posterolateral spondylodesis in treatment of unstable lumbar spine burst fractures. The lumbar fractures were fixed using posterior universal spine system (USS) instrumentation. Bioactive glass was implanted on the left side of the fusion bed and AB on the right side. A solid bony fusion was seen on CT scans on the side of the AB implantation in all 10 patients. Resorption of the implanted graft was mild ($n = 7$) or absent ($n = 3$). On the BAG implantation side, a solid fusion on CT scans was only seen in 50% of patients. Resorption of BAG was mild ($n = 3$), moderate ($n = 2$) or evident ($n = 5$). Bioactive glass granules were still partially visible in six out of 10 patients on CT scans.

Abdullah et al.⁸² performed a systematic review to evaluate the available literature supporting the use of lumbar fusion extenders in clinical practice. A review of English-language literature was performed between 1990 and January of 2010 for all literature presenting clinical outcomes of lumbar fusion extenders. After controlling for inclusion and exclusion criteria and assigning levels of evidence, 19 clinical studies were fully reviewed including those for DBM, rhBMP-2, f3-TCP and calcium sulfate. The investigators found that the most extensively studied of the lumbar fusion extenders is β -TCP, especially with

regard to its use in adolescent scoliosis correction. The use of rhBMP-2 and DBM as extenders was supported only by two and three clinical studies, respectively. Calcium sulfate and other miscellaneous extenders were not conclusively or consistently supported by available clinical studies.

Alsaleh et al.²⁸ performed a systematic review to evaluate the efficacy, safety and outcomes of osteoconductive BGEs compared with ICBG in posterolateral thoracolumbar spinal fusion. An electronic literature search was conducted through April 2011 using MEDLINE, EMBASE, CENTRAL and Cochrane Library. Risk of bias and methodological assessment was performed. Study design and result heterogeneity was also analyzed. Pooled weighted relative risk (RR) ratios were calculated to compare fusion and adverse event rates. Weighted standardized mean differences were calculated to compare functional outcome and pain scores. Thirteen studies were included representing a total of 768 patients. Overall study quality was low (mean Cochrane Risk of Bias score, 4.8 out of 12; range: 3–6). Fusion rates were comparable between the BGE and ICBG groups (RR = 0.96; 95% confidence interval [CI]: 0.89–1.03; $p = 0.28$). There was substantial heterogeneity in the pooling of studies. The pooled rate of donor site pain in the ICBG group was 11.2% (95% CI: 7.4–15.1%). Reported adverse events, excluding donor site pain, were significantly lower in the BGE group (RR = 0.42; 95% CI: 0.28–0.64; $p < 0.0001$). Functional outcomes were not significantly different between the two groups. The authors concluded that osteoconductive BGEs combined with local spine autograft and/or BMA have comparable fusion rates, similar functional outcomes, lower complication rates and a lower risk of donor site pain than ICBG. Caution should be taken in interpreting these findings, given the low quality of the studies and the heterogeneity in the results. Randomized controlled studies using blinded assessments are required to help elucidate more conclusive evidence.

OSTEOPROMOTIVE AGENTS/GROWTH FACTORS

Bone repair and spinal fusion are highly orchestrated processes involving myriad growth factors. These proteins may be produced locally at the site of bone formation or may be delivered by chemoattracted circulating cells such as the lymphocyte, the platelet and the macrophage. While myriad growth factors have been implicated in the process of spinal fusion, only two are currently clinically available.

These are the BMPs, 2 and 7 and PRP. The BMPs are the focus of another chapter in this textbook, and so will not be discussed here.

Platelet-rich plasma is defined as a portion of the plasma fraction of autologous blood having platelet concentrations above baseline. When activated, the platelets release growth factors that play an essential role in bone healing such as PDGF, TGF- β , VEGF and others. Multiple basic science and in vivo animal studies agree that PRP has a role in the stimulation of the healing cascade in ligament, tendon, muscle cartilage and in bone regeneration. However, the results of clinical studies in spinal fusion have been less than encouraging, and currently there is no evidence to recommend their use in routine clinical practice.

Sys et al.⁸³ examined the efficacy of PRP in monosegmental posterior lumbar interbody fusion. Forty patients were recruited for the study fulfilling strict entry requirements and were randomized with a 1:1 ratio. In each group, one patient was lost to follow-up. Thirty-eight patients completed the VAS, the ODI questionnaires and the SF-36 preoperatively and postoperatively at 3, 6, 12 and 24 months, respectively. Computed tomographic scans of the lumbar spine were taken at 3, 6 and 12 months. Posterior stabilization was achieved with pedicle screws and interbody fusion was aimed at with carbon cages filled with autologous bone. Baseline demographic data (age, sex, smoking history, preoperative outcome measures) showed no relevant difference between groups. For patients who received autograft only, the mean VAS improved by 4.0 points ($p < 0.01$), mean ODI improved by 32.1 points ($p < 0.001$) and mean SF-36 showed statistically significant improvement in each of the eight domains and in the physical ($p < 0.001$) and mental ($p < 0.001$) component summary measures. For patients who received autograft with PRP, the mean VAS improved by 4.92 points ($p < 0.01$), mean ODI improved by 30 points ($p < 0.001$) and mean SF-36 showed statistically significant improvement in six of the eight domains ($p < 0.02$) and in the physical ($p = 0.016$) and mental ($p < 0.001$) component summary measures. The improvement in the VAS score and the physical component summary score was more pronounced in patients who received autograft with PRP. These differences were, however, not statistically significant. Computed tomographic scans showed uneventful osseous healing in all but one patient with no difference between groups. In this prospective randomized controlled clinical and radiological trial, adding PRP in posterior lumbar interbody fusion did not lead to a substantial improvement or

deterioration when compared with autologous bone only. No inhibitory effect of PRP was observed on CT scans. The authors concluded that from a clinical and radiological point of view, the use of PRP seems to be justified in posterior lumbar interbody fusion surgery. From an economical point of view, however, the expense of using PRP cannot be justified until statistical significance can be reached in a larger study.

Acebal-Cortina et al.⁸⁴ analyzed, if the adding of autologous platelet concentrate (APC) to a mixture of local autograft plus TCP and HA (TCP/HA) would improve the fusion rate in posterolateral lumbar fusion. They performed a prospective, controlled, blinded, nonrandomized clinical trial in 107 patients affected by degenerative lumbar pathology. The study group consisted of 67 patients, in which autologous platelet concentration was added to a mixture of autologous LBG and TCP/HA. A control group of 40 patients with same pathology and surgical technique but without APC addition was used to compare the fusion mass obtained. By means of plain X-rays, a blinded evaluation of the intertransverse fusion mass quality at 12 and 24 months was made according to type A (bilateral uniform mass), type B (unilateral uniform mass) and type C (irregular or lack bilateral mass). Patients with type C were regarded as pseudarthrosis. In the study group, 17 patients had lack or irregular fusion mass (25.4%) versus three patients in the control group (7.5%), which was statistically significant. This study shows that the adding of autologous platelet concentration to a mixture of autologous bone graft plus TCP/HA has decreased our rates of posterolateral lumbar fusion.

CELL-BASED THERAPIES

Cells are key players in bone regeneration. Osteoblasts produce osteoid, an extracellular protein-based matrix, which mineralizes to become bone. Osteoprogenitor cells or MSCs can differentiate into osteoblasts and induce bone formation. Currently, two ways exist to prepare cells for clinical application, each with their advantages and disadvantages. One method is to concentrate cells immediately in the operating room and place them directly on the site of injury. Unfortunately, only low cell numbers can be generated by this process. Another method is to expand the cells in vitro. By this method, a very large number of cells can be generated. The two-step method has two disadvantages: one additional exposure to anesthesia is

required for reimplantation of the cells, and there is a risk of an *ex vivo* cell dedifferentiation and infection during the cell expansion.

Currently available cell-based bone graft substitutes include BMA and MSCs. These options lack osteoconductive or structural material properties and so must be used in combination with biological scaffolds (allografts and autografts) or with synthetic carriers. Bone marrow aspirate contains osteoprogenitor and hematoprogenitor cell populations. It is easily obtained from the posterior iliac crest and from vertebral bodies. The paucity of evidence for the use of BMA has already been discussed.

Mesenchymal Stem Cells

Stem cells have two essential fundamental characteristics: the ability for self-renewal and the ability to differentiate into a variety of cell phenotypes. Stem cells are loosely categorized as being either adult or embryonic depending on their origin. The bone marrow contains both MSCs and hematopoietic stem cells. The latter have been used clinically for many years, predominantly in the treatment of hematological malignancy. Iliac crest bone grafting is a form of autologous MSC transplantation. Autologous transplantation of MSCs has a similar potential for donor site morbidity, with an additional major issue being that, following harvest, the cells require *in vitro* expansion. This introduces added cost of individual culture expansion, regulatory hurdles and logistical impediments, as surgery using these cells is delayed by several weeks from the time they are harvested. Furthermore, autologous cells are of variable quality depending on the protoplasm of the patient.^{85,86}

Allogeneic cell transplantation overcomes these problems, as an “off the shelf” product, with batch-to-batch consistency, can be used as needed. The potential for transmission of infection and rejection are the obvious concerns of an allogeneic approach; however, donor screening and extensive testing of the cells, in a similar manner employed for blood transfusions, minimizes the infection risk. The rejection risk is minimal as mesenchymal cells are of low immunogenicity.

Mesenchymal stem cells can be isolated from various tissues and under the correct *in vitro* culture conditions can be preferentially differentiated into an osteogenic lineage of cells that produce osteoid.⁸⁶

Khashan et al.³⁴ performed a systematic review of the literature attempting to answer a number of KQs:

1. Does the use of MSCs or BMA combined with synthetic or allograft extenders contribute to thoracolumbar fusion rates that are comparable to the rates achieved by the use of iliac crest graft?
2. Are these fusion rates comparable to those of LBG?
3. Is the addition of stem cells (SC) or BMA to ICBG or LBG contributes to better thoracolumbar fusion rates?
4. Are the cervical spine fusion outcomes achieved by the use of SCM or BMA with synthetic or allograft scaffolds comparable to the ICBG or LBG outcomes?
5. Was there any difference in terms of fusion rates, when MSCs were used as compared to BMA?

In this systematic review, the authors found that clinical studies were only available for BMA and not for MSCs.

A recent preclinical study designed to assess the safety and efficacy of mesenchymal pluripotent stem cells (MPC)-facilitated cervical interbody fusion in a sheep⁸⁷ model showed no cell-related adverse events, including absence of swelling, airway compromise or neural compression. MPCs were added to a commercially available TCP/HA carrier and were demonstrated to promote a faster and more robust fusion than current clinical treatments using autograft or carrier alone.

Nakajima et al.⁸⁸ investigated the effectiveness of graft material for spinal fusion using a rabbit model by examining the MSC with or without osteogenic differentiation. Japanese white rabbits were divided into four groups: (1) autologous bone (AG), (2) HA, (3) MSC and (4) osteogenic MSC (OMSC). Each group underwent fusion of the intertransverse processes. The lumbar spine was harvested en bloc, and the fusion mass was evaluated radiographically, by manual palpation test and by histologic analysis at 6 weeks after surgery. Fusion success or failure was assumed based on the results from manual palpation of the harvested spine. Four of five rabbits in the OMSC group, four of six rabbits in the AB group, two of six rabbits in the MSC group and none of six rabbits in the HA group achieved fusion. In the OMSC group and AG group, new bone formation was observed histologically. In the HA group, fibrous tissue and cartilage were observed and there was no new bone. In the MSC group, less mature bone formation was present in the grafted fragments. The study suggested that MSCs that have been cultured with osteogenic differentiation medium may induce the formation of new bone in experimental spinal fusion.

Risbud et al.⁸⁹ evaluated the osteogenic potential of MSCs isolated from the bone marrow of the human vertebral body (VB). Marrow samples from VB of patients

undergoing lumbar spinal surgery were collected; marrow was also harvested from the IC. Progenitor cells were isolated and the number of colony forming unit-fibroblastic (CFU-F) determined. The osteogenic potential of the cells was characterized using biochemical and molecular biology techniques. Both the vertebral body (VB) and iliac crest (IC) marrow generated small-, medium- and large-sized CFU-F. Higher numbers of CFU-F were obtained from the VB marrow than the IC ($p < 0.05$). Progenitor cells from both anatomic sites expressed comparable levels of CD166, CD105, CD49a and CD63. Moreover, progenitor cells from the VB exhibited an increased level of alkaline phosphatase activity. Mesenchymal stromal cells of the VB and the IC displayed similar levels of expression of Runx-2, collagen type I, CD44, activated leucocyte cell adhesion molecule (ALCAM) and osteocalcin. The level of expression of bone sialoprotein was higher in MSC from the IC than the VB. VB and IC cells mineralized their extracellular matrix to a similar extent. These studies showed that CFU-F frequency is higher in the marrow of the VB than in that of the IC. Progenitor cells isolated from both sites respond in a similar manner to an osteogenic stimulus and express common immunophenotypes. Based on these findings, the authors propose that progenitor cells from the lumbar vertebral marrow would be suitable candidate for osseous graft supplementation in spinal fusion procedures. They suggested that studies must now be conducted using animal models to ascertain, if cells of the VB are as effective as those of the IC for the fusion applications.

Hormonal/Gene Therapy

Gene therapy is an interesting tool used to accomplish the local delivery of beneficial growth factors for bone regeneration. Genetic modification of cells can have advantages compared with the simple supplementation of cytokines or growth factors. First, the selected proteins have a short half-life. Second, a single administration is usually not sufficient for a biological effect. Third, the costs for the required quantities of protein would be prohibitively high. Fourth, continuous protein synthesis by genetically modified cells increases the likelihood for the desired effect. Genetically modified autologous MSCs, (over) expressing osteogenic growth factors or cytokines, provide both autocrine and paracrine stimuli to induce and maintain osteogenic differentiation and are therefore promising cellular components for protocols aimed at site-specific bone

repair. In addition, the systemic or intraosseous marrow reimplantation of autologous MSCs genetically “corrected” for any skeletal degeneration-causing mutation could help to solve problems of limited availability and suboptimal engraftment of allogeneic MSCs.⁹⁰⁻⁹³

There are both viral and nonviral methods to accomplish the above, with the viral methods showing a higher transfer efficiency of target genes. Currently, due to safety reasons, only animal models exist to evaluate gene therapy for fracture healing. An interesting method being developed for future clinical use is the ex vivo adenoviral transduction of tissue grafts to continuously deliver growth factors such as BMP-2 over a limited period needed for fracture healing.

In addition to local agents, the systemic use of hormone therapy in fracture healing is under investigation. Growth hormone appears to have a positive influence on fracture healing in animals and humans. Parathyroid hormone (PTH) has been shown to have a positive effect on fracture healing, especially for osteoporotic bones.

The latest large animal investigations have reported improved bone defect healing by local delivery of PTH. In addition to binding PTH to fibrin, incorporating PTH to biomimetic calcium phosphate coating also offers a potential option for future therapies in humans. At this time, hormone therapy for human fracture healing is only under off-label use as further investigation into the appropriate dosages and safety factors is still necessary.⁹⁴

Hirsch et al.⁹⁵ performed a systematic review to evaluate the available evidence on the potential impact of bisphosphonates and PTH on fusion rate and fusion quality in spinal arthrodesis. The literature contained 18 animal studies and one clinical trial investigating the impact of these medications on spine fusion. Most animal studies evaluating the impact of bisphosphonates on fusion rate have not found statistically significant changes with treatment, although this fact may be attributable to low statistical power. The animal literature does suggest that bisphosphonate therapy results in a less histologically mature fusion mass; however, the impact of these changes on fusion mass biomechanics is unclear. The only available human study suggests that these bisphosphonates may increase the radiographically defined fusion rate but did not demonstrate an impact on clinical outcome. In animals, PTH improves the fusion rate and fusion mass microstructure, but data on its effect on fusion mass biome-

chanics are lacking. No studies have evaluated the impact of PTH on spine fusion in humans.

CONCLUSION

This review provides the physician/surgeon with:

1. A clinically relevant review of the biology of spinal fusion and bone grafting,
2. A comprehensive consideration of the currently available bone graft substitute options and
3. A conceptual framework for the analysis and evaluation of future studies.

Although many of the studies reviewed here have shown at least equivalence of numerous bone graft substitute options to iliac crest, there is insufficient evidence to recommend them over the gold standard. For most products, the quality of the scientific evidence is low, with the bulk of the studies being retrospective case series or at best underpowered prospective cohort studies. Inconsistent study design and lack of proper control groups has meant that much of the published literature is not comparable, making meta-analysis impossible and systematic review challenging.

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Vascularized Bone Grafts in Spine Surgery

Gregory Gebauer

Snapshot

» Indications

» Sources of Vascularized Autograft

INTRODUCTION

Achieving a solid bony fusion is necessary for the successful outcome of many complex, reconstructive spinal operations. The use of bone grafts is common in these procedures, both to help achieve a bony fusion and to provide structure support. There are many types of grafts, including local autograft, harvested bone graft obtained through a separate incision (such as iliac crest autograft), allografts and demineralized bone grafts. All of these have been shown to be effective and play an important role in surgery on the spine. However, in the setting of complex pathology, such as infection or spinal tumors, or in patients predisposed to poor bony healing, achieving such a fusion using these grafts can be difficult. The use of vascularized bone graft offers many advantages that may help to overcome these challenges.

Allografts and nonvascularized autografts are remodeled into a solid fusion by the process of creeping substitution. In this process, the bone is revascularized, reabsorbed by osteoclasts and finally remodeled into reactive bone. This process can take months or years and complete incorporation may never occur. Additionally, during the initial remodeling phases the grafts are structurally weaker due to the increased porosity of the bone.¹ It has been estimated that fatigue fractures occur in 16–20% of structural allografts^{2,3} and in up to 50% of anterior grafts over 4 cm in length.⁴ Vascularized autografts, by maintaining their blood supply, keep the osteocytes viable.⁵ This allows them to forego an extensive remodeling process and maintain their structural integrity.^{6–8} Additionally,

vascularized grafts respond to mechanical stress with hypertrophy, resulting in increased stiffness over time.^{9–11} The harvesting and placement of vascularized bone grafts is however technically demanding and can involve microsurgical techniques not familiar to most spine surgeons.

INDICATIONS

There are no clear indications for when a vascularized graft should be used. For most patients, standard bone grafting and surgical technique should be sufficient. Typically, patients requiring vascularized bone graft will have relatively unique and special circumstances that impair normal bone healing. Shin and Dekutoski suggested four indications:¹²

1. Multiple level corpectomy, typically for tumor resection.
2. Failed previous spine arthrodesis secondary to osteomyelitis or neurofibromatosis.
3. Poor osseous and soft tissue bed secondary to radiation exposure necrosis.
4. Failed fusion in neuromuscular disease, such as Charcot arthropathy.

For patients with spinal tumors, the prior use of radiation or the need for postoperative radiation for local tumor control has been shown to have a negative effect on graft incorporation and healing.

These recommendations are not, however, without some controversy. Bradford and colleagues have suggested that vascularized grafts should not be used in patients with tumors.^{13,14} Their concern is that the increased blood flow from the vascularized graft could supply the tumor

cells and lead to local recurrence or lead to metastasis if tumor cells carried through the blood stream. Others have argued that this is more of a concern during intralesion tumor excision and that there is less concern if tumor is removed en bloc.¹²

SOURCES OF VASCULARIZED AUTOGRAFT

Multiple sources of vascularized autograft have been described. These include the ribs,^{4,14} fibula,^{12,15} scapula,¹⁶ iliac crest,¹⁷ tibia,¹⁸ and distal radius.¹⁹ They have been utilized throughout the appendicular skeleton and in the head and neck to treat multiple different pathologies, including tumors, trauma, nonunions, osteonecrosis, and congenital defects.^{17,19-22} Rib and free fibula grafts are the most common donor site for vascularized grafts in spine surgery. The rib graft has the advantage of its close anatomical location to the spine. This allows the bone to be transferred on its vascular pedicle without the need for microsurgery. This also limits the location where the graft can be used to the thoracic spine and thoracolumbar junction. Additionally, the curved shape and thin size of the ribs mean that they may not always be appropriate for anterior strut grafting. Free fibula grafts offer better mechanical properties and can be placed anywhere within the spine; however, they require a microvascular anastomosis to reconnect the blood vessels and require a second surgical site for graft harvest.

Vascularized Rib Graft

The close location of the ribs and their vascular pedicles make the local transfer of the vascularized bone to defects in the thoracic spine possible. While the rib does not have the structural integrity to serve as an anterior strut graft, the vascularized bone can be used as an “on-lay” graft to supplement anterior fusion or for posterior fusion between the transverse processes.²³⁻²⁸ The curvature of the ribs may fit the nature kyphotic posture of the thoracic spine or may need contouring for optimal positioning.

Rib graft can be harvested from either the prone or the lateral position, depending on the exposure needed for the primary procedure. A wider area around the rib cage should be included in the surgical field; however, in most cases adequate graft can be obtained from the standard incisions used to approach the spine. The size of the defect requiring grafting should be measured. An additional

2–3 cm of graft should be planned to be harvested. The rib selected should be on the ipsilateral side as the defect or can be bilateral if a posterior approach is used. The rib selected should be either from the superior or inferior margins of the defect and may depend on the location of the defect. The most upper (1–4) and lower ribs (11 and 12) may not offer sufficient length for graft material. Generally, the middle ribs make for the best donor graft.

Once the rib is selected, the anterior point for the rib resection is identified. The intercostal vessels are ligated distal to this point. The anterior rib can then be cut. The rib is then mobilized from lateral to medial with care taken to preserve the intercostal vessels. Proximally, the vascular bundle is freed down to its connection to the aorta. This may require mobilizing the vascular pedicle from the most medial aspects to the rib, just lateral to the rib head to allow for better mobility. The medial rib is then separated at the rib head and rotated on its pedicle into the defect.

The graft can now be prepared to be seating into the defect. If necessary, unicortical cuts can be created on the concave portion of the rib using a small oscillating saw and allowing the graft to be straightened¹² (Fig. 33.1). Lewis et al. have described a technique for step-cut osteotomies for use in posterior grafting.²⁵ Using their method, a concave, saddle cut is made at the distal end of the graft that is seated on the pedicle at the inferior margin of the defect. A step-cut is then made at the proximal end. This is seated under the transverse process or lamina at the superior edge of the defect. Once positioned gentle compression can be used to secure the graft and posteriorly placed instrumentation can be used to help secure the graft in place.

Clinical Results—Rib Graft

The results of several case series using vascularized rib graft to augment fusion in reconstruction of the thoracic spine have been published. Wilden et al. reported on a series of 18 patients.²⁶ They reported that all the patients went on to fuse at average time of 6.8 months and that there were no complications related to the graft harvest. Lewis reported on a series of 17 patients using their step-cut technique.²⁵ Of these, 8 used vascularized rib grafts and 9 used nonvascularized grafts. Of the 8 patients with a vascularized rib graft, 4 died due to their underlying disease (cancer). The remaining 4 demonstrated graft integration and no loosening or subsidence at approximately 4 years from surgery.

Similar results are also available for anterior vascularized rib grafts. Govender et al. followed 8 children with Pott’s disease for a minimum of 10 years and reported

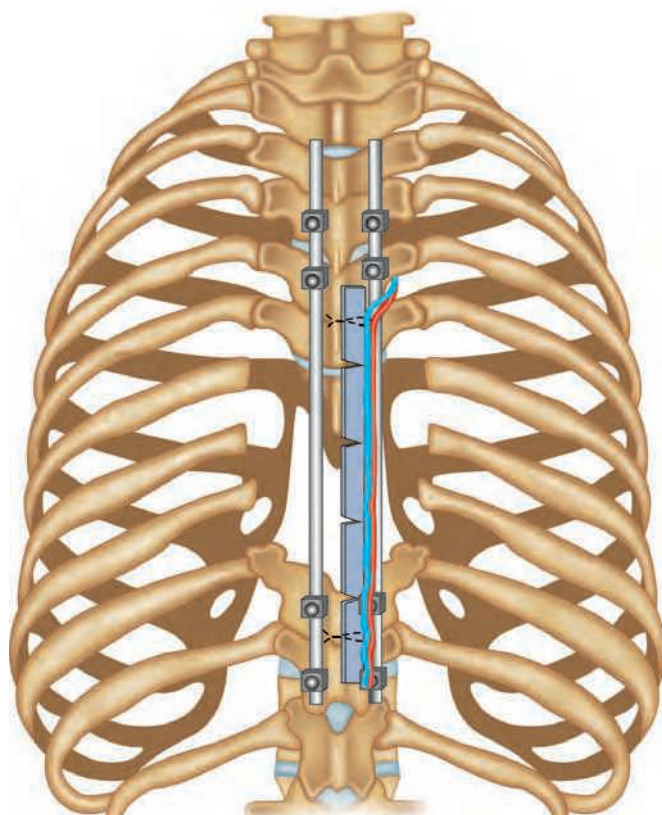


Fig. 33.1: Placement of vascularized rib graft for posterior spinal fusion. Note the cuts made along the bone to allow for straightening of the normally curved rib.

bone fusion in all cases.²⁷ Nakamura et al. reported on 23 adult patients with anterior vascularized rib graft.²³ In this series, the graft was folded on itself to form 3 or 4 pieces all connected on the same pedicle. They reported bony fusion in all cases without the use of additional bone graft or extenders.

Free Fibula Graft

The fibula has many features that lend to its suitability as a vascularized bone graft. The fibula can be harvested with minimal donor site morbidity. Its peripheral location makes harvest relatively simple. Its vascular pedicle is large enough (2–3 mm) to allow for the anastomosis. In addition, it is a relatively straight bone with excellent mechanical strength, allowing it to be used as a structural support.

Before performing a vascularized fibular graft, careful preoperative planning should be performed. This includes assessments of both the donor site and the recipient bed. At the recipient bed, a vessel capable of accepting

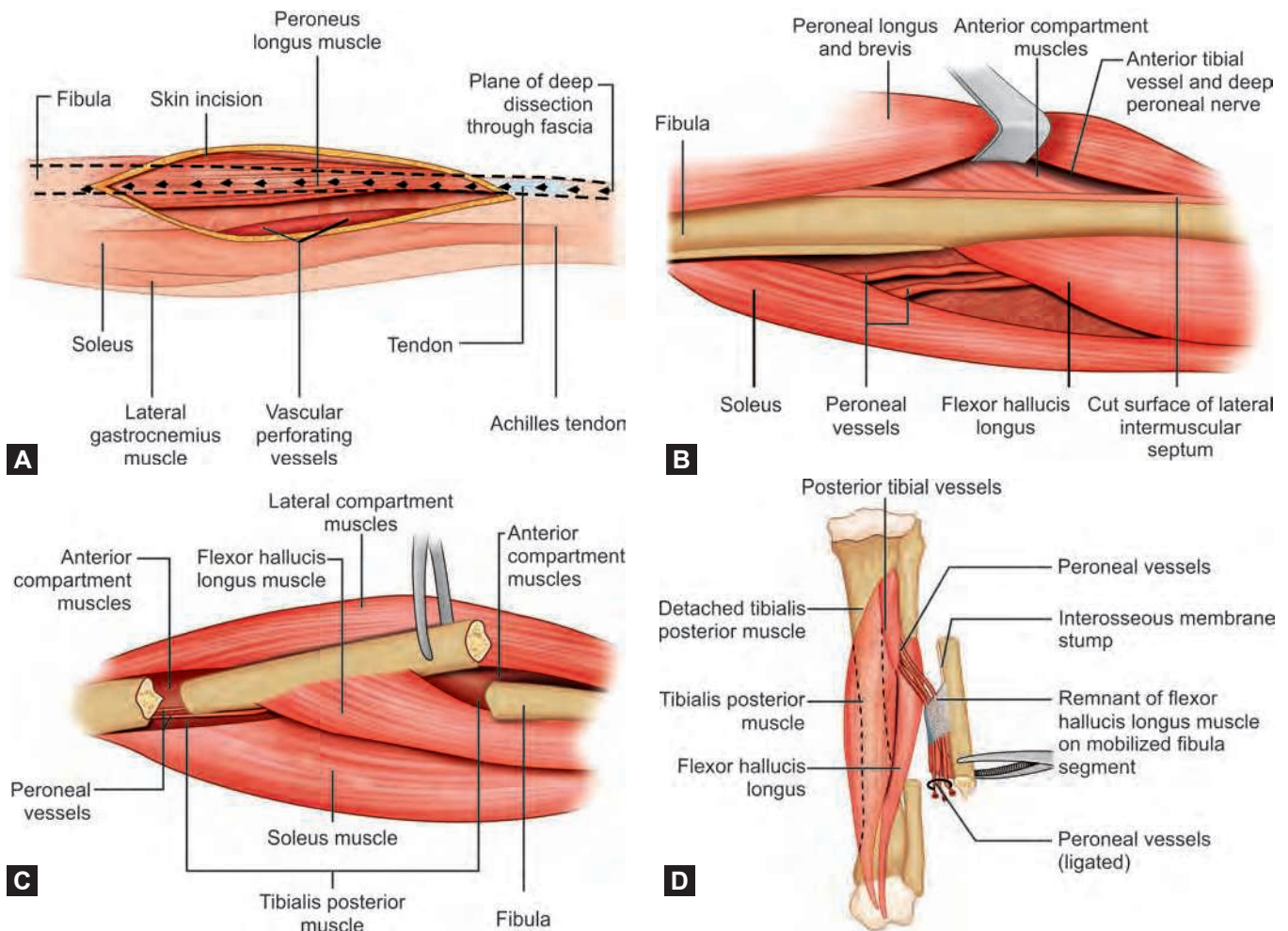
the anastomosis should be identified. This may require computed tomography (CT) or magnetic resonance (MR) angiography. The surgical approach should be selected to allow for access and visualization of both the spine and the anastomosis site. The length of the defect to be grafted should be measured as this will determine the amount of fibula necessary to harvest.

The donor site should also be carefully evaluated. The presence of abscess or any other injuries, infections or conditions that may affect the leg should be identified. The vascularity of the limb must also be assessed. Some authors have recommended the use of angiography for all patients being considered for this procedure.²⁹ Others rely first on physical examination.²⁰ In this technique, the presence and quality of both dorsal pedal and posterior tibial pulses is first checked. If one or both pulses are abnormal or absent, further evaluation by ultrasound or angiography is then performed. Finally, if there are no restrictions forcing the use of only one limb, the right or left side can be selected on the ease of access depending on how the patient is positioned during the surgery, i.e. if the patient is in the right-side decubitus position with the left side up then it is easier to harvest the left fibula.

The surgical technique for graft harvest has been well described by Woods and others (Figs. 33.2A to D).^{20,30,31} Once positioned for surgery, a tourniquet should be applied to the upper thigh. The remaining limb, from above the knee to the toes, should then be prepped and draped. The fibula should be marked along its entire length. The main nutrient artery is generally found between the junction of the middle and proximal third and the midpoint of the fibula. The incision should be centered at this point. The amount of graft necessary can then be measured. An additional 5–6 cm should be taken to ensure adequate bone harvest.

A linear incision is made along the length of the fibula and dissection carried out down to the fascia. The lateral and posterior muscle compartments are identified. In the distal portion of the incision, the peroneus longus tendon is identified. Posterior to the tendon a thin layer of adipose tissue can be seen. This marks the plane between the lateral muscle compartment and the soleus muscle in the posterior compartment. Several perforating vessels cross this plan. If an osteocutaneous flap is planned, these vessels should be spared. Otherwise they can be ligated.

Dissection is then continued proximally, identifying the soleus muscle. This can be elevated posteriorly off the fibula. Care should be taken as the peroneal vessels are



Figs. 33.2A to D: Surgical dissection of the vascularized fibula graft: (A) superficial dissections; (B) deep dissection, with care taken to identify and preserve the peroneal vessel; (C) lateral and (D) anterior diagrams of the harvested fibula graft and vessels.

located just deep to the proximal soleus. These vessels should be visible in the proximal incision after the soleus is detached. Attention is then returned to the distal portion of the incision. Here, the peroneal muscles are elevated. The flexor hallucis longus (FHL) muscle should be left in place to help protect the peroneal vessels until they can be identified and dissected later in the procedure. It is also important to identify and protect the superficial peroneal nerve during dissection of the peroneal muscles. If it is necessary to take the proximal fibula, the common peroneal nerve should be identified and protected. Once the peroneal muscles are separated, the septum between the lateral and anterior can be sharply incised and the anterior muscles elevated off the fibula and interosseous membrane. The anterior tibial vessels and the deep peroneal nerve lie within this plane and should be protected.

At this point, the planned length of fibula to be taken should be measured and marked. Care should be taken to include the middle third of the bone to ensure that the main nutrient artery is included within the segment to be harvested. The proximal osteotomy is created first. Retractors should be placed around the bone to protect the vessels and soft tissues. A gigli or small oscillating saw can be used. A small amount of the FHL muscle is then elevated in the area of the distal osteotomy. The retractors can then be placed, and the osteotomy again can be created with a saw.

An additional 1–2 cm of the FHL muscle should then be elevated. At this point, the fibula can be gently retracted anteriorly and the peroneal vessels should now be visible deep to the FHL muscle at the distal portion of the incision. The distal peroneal vessels can then be ligated and

sectioned. The fibula should then be externally rotated to expose the interosseous membrane. The membrane can now be released from proximal to distal revealing the tibia-lis posterior muscle. This muscle can be then elevated with care taken to preserve the peroneal vessels that lie deep into the muscle. The peroneal vessels should now be visible. Many arterial and venous branches should be visible. Any medially directed branches can be ligated. Any laterally or posteriorly directed branches or any branches that enter into the FHL muscle should be preserved. Except for the portion directed adjacent to the vessels, the remaining FHL can now be elevated.

At this point, the peroneal artery and veins should be isolated in the proximal incision. Additional mobilization of the vessels can be achieved by dissecting them off the proximal portion of the graft. Minor periosteal branches can be ligated, but care should be taken to preserve the main nutrient artery. In most cases, a pedicle length of 6–8 cm should be achievable. The proximal peroneal vessels should then be isolated with vessel loops. At this point, Wood recommends deflating the tourniquet and allowing the graft to reperfuse for at least 5–10 minutes or until the recipient site is ready.

Following harvest of the graft, the incision site is closed in standard fashion. The fascia can be left open to minimize the risk of postoperative compartment syndrome. Drains can be used at the surgeon's discretion. Some authors have advocated reconstruction of the fibular defect, either with beta-tricalcium phosphate³² or by bone grafting the site using any redundant portions of the fibula not used at the recipient site.³³ Both of these studies were limited in size (14 patients in the beta-tricalcium phosphate study and 10 in the experimental arm of the bone graft study). Arai et al. evaluated the use of beta-tricalcium phosphate using only radiograph and subjective measures.³² They reported bony union in only 2 of 9 adult patients and 3 of 5 pediatric patients. While none of the pediatric patients reported limitations, many of the adults reported problems with walking (4), running (11) or jumping (11) despite the bone graft. Patients treated with bone graft reconstruction showed increased ankle dorsiflexion strength when compared to control subject who did not receive bone graft. There were no other objective differences in ankle strength and no difference in patient satisfaction scores. The authors concluded that the given additional operative time, postoperative weight-bearing restrictions, and potential for additional complications that reconstruction with bone graft may not be worth the cost.

Graft Insertion

Exposure of the recipient site should be carried out simultaneously with harvest of the fibula using two separate surgical teams. Appropriate bony resection and endplate exposure should be performed. The site of the anastomosis should also be exposed. The appropriate vessels should be isolated with vessel loops to maintain control. Several potential anastomosis sites are available for the placement of the fibula graft and depend on the location within the spine where the graft will be placed. Commonly used vessels include the external carotid artery and jugular vein (C1–C7),³⁴ superior thyroid artery (C3–C7),³⁵ the internal thoracic artery and vein (levels C7–T3),³⁶ the segmental renal artery and vein (T12–L1),³⁷ the lumbar segmental artery and retroperitoneal veins (L1–L5),³⁸ the iliac artery and vein (for anterior approaches to the lower lumbar levels and sacrum),³⁰ and the gluteal artery and vein (posterior approach to the lower lumbar levels and sacrum).³⁹ Multiple other anastomosis sites exist and can be used based on specific patient circumstances.

Generally speaking, it is advantageous to position the graft prior to performing the anastomosis to allow for better stability (Fig. 33.3). If there is enough length of the fibula, 1–2 mm section of the center of the bone can be removed (with care taken to preserve the vessels and soft tissues)

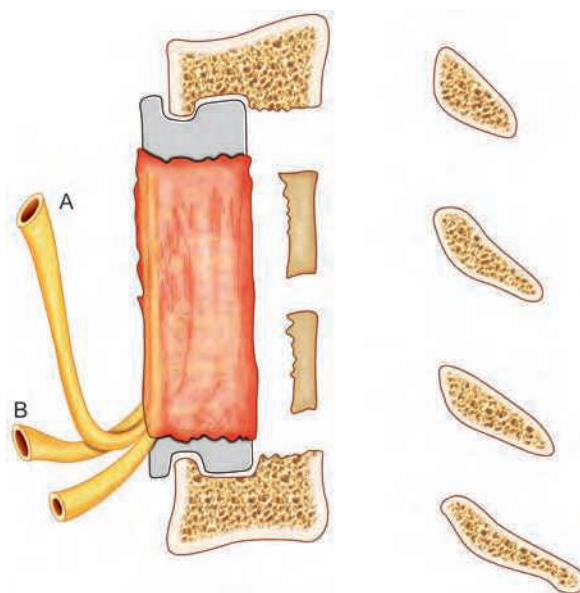


Fig. 33.3: Diagram of a vascularized fibula positioned in the cervical spine. Note the notches in the graft to minimize dislodgement. Vascular structures include (A) the peroneal artery and (B) the peroneal veins.

and the graft folded on its self to create a “double barrel” graft.³⁰ This allows for increased surface area and structural support. The graft may be trimmed as necessary to allow for placement; however, sufficient force should be necessary for graft placement to minimize the risk of later dislodgement. Care should be taken to make sure that the vascular pedicle is not compressed or torqued after insertion. If additional vessel length is needed for the anastomosis, the saphenous vein can be harvested and used as an interpositional graft.^{40,41} Once the anastomosis is complete any necessary instrumentation can be performed either at that time or from a secondary approach.

Postoperative Monitoring

Monitoring of an osteocutaneous flaps is relatively easy; the exposed skin can be evaluated for the presence of capillary refill and brisk bleeding from pin pricks to the skin. Evaluation of deep grafts is more difficult. Depending on the location of the anastomosis, a duplex ultrasound can be used; however, this is often difficult in spinal reconstruction due to the depth of the graft and the surrounding vessels that may interfere with the signal.⁴² Bone scintigraphy is the most commonly used tool for evaluating deep free bone grafts.^{43,44} Bone scintigraphs will generally become positive 7–14 days after surgery. Studies evaluating the use of bone scintigraphs in patients undergoing vascularized fibula graft for the treatment of avascular necrosis of the femoral head suggest that increased signal strength correlates with graft survival.⁴⁴ Dynamic enhanced MR imaging and single photon emission CT have also been shown to be valuable in the assessment of grafts placed for avascular necrosis.⁴⁵ While these imaging modalities are useful for predicting clinical outcome, they unfortunately are costly and time consuming and lack the ability to any regular, “real-time” monitoring of the graft that would allow for timely correction of any graft occlusion or venous congestion.

Clinical Results—Free Fibula Graft

The efficacy of free fibula grafts in the treatment of osteonecrosis of the hip and in reconstruction of the extremities has been well established.^{22,31,46–48} While there has been no larger study evaluating the use of vascularized fibula graft in spine surgery, many case reports and small clinical series have been published. A summary of these studies appears in Table 33.1. Most commonly, vascularized fibula grafts have been used for patients with

infections or with tumors, particularly those who have undergone preoperative or who will be undergoing postoperative radiation. Previous animal and human studies have demonstrated increased rates of pseudarthrosis in patients who have received radiation,^{49,50} with the highest incidence seen in patients receiving doses of 4,000 cGy or more. Moran et al. reported on a series of 12 patients who underwent free fibula bone grafting.⁵¹ Six of these grafts were performed purely for pathology occurring within the spine and the other 6 for combined spinopelvic defects. One patient died during the immediate postoperative period after an myocardial infarction (MI), and another had failure of his flap requiring a hemipelvectomy. Of the remaining 10 patients, 9 went onto fusion at an average of 4.5 months. The remaining patient required revision grafting but ultimately went onto fusion as well. In the series by Wuisman et al., 8 patients were treated with free fibula autograft, 4 of whom had tumors.²⁴ One patient died in the perioperative period from an unknown cause. All of the remaining 7 patients went onto fuse at an average of 4.5 months. Lee et al. published a series of 6 patients, 4 of whom were treated for tumors.³⁴ One patient died due to intraoperative hypotension and another whose graft failed due to thrombosis. This was revised with a second free fibula graft. Ultimately, all 5 surviving patients went onto fusion. A similar study by Ackerman on 7 patients (3 with tumors) showed fusion on 6 patients at an average of 3.2 months.³⁰

Many of the above studies also included patients who were treated for osteodisks/osteomyelitis. High rates of union were also seen in these patients. Erdman et al. specifically looked at the use of vascularized fibula grafts in patients who had infections and who had had previous spine surgery including anterior instrumentation.⁴¹ All four of the patients cleared their infection following surgery and a course of antibiotics. Three of the four went onto fusion without the need for any additional procedures. One patient, who was initially treated with anterior fibula grafting from L1 to L3 without instrumentation went onto nonunion at the cephalad level. This was treated with posterior fusion and instrumentation using iliac crest bone graft from T12 to L4. The patient subsequently went onto heal. Vascularized fibula grafts have been used to successfully treat infections in cervical spine as well.⁵⁵

Smaller cases reports and series have also looked at the effectiveness of vascularized fibula grafts in the treatment of deformity. Meyers et al. reported on pediatric patient with a grade 4 spondylolisthesis at the L5-S1

Table 33.1: Summary of case reports and case series of patients undergoing vascularized fibular autograft as an adjunct to spinal fusion surgery.

Author	Number of patients	Number of spine patients	Anatomic location	Pathology	Prior radiation	Mortality	Complications	Fusion rate	Mean time to fusion, mo	Mean length of follow-up, mo
Ackerman et al. ³⁰	7	7	Thoracic and lumbar	3 tumor, 4 osteomyelitis	Yes	0	1 graft failure—venous thrombosis	86%	3.2	38
Kim et al. ⁵⁴	3	3	Thoracic and lumbar	1 osteomyelitis, 1 pathologic fracture, 1 iatrogenic kyphosis	No	0	0	100%	NR	24
Doi et al. ³⁵	6	6	Cervical	4 OPLL, 2 spondylotic myelopathy	No	0	0	100%	3.4	26
Asazuma et al. ⁵²	1	1	Cervical	Kyphosis due to neurofibromatosis type 1	No	0	0	100%	5	NR
Lee et al. ³⁴	6	6	Thoracic and lumbar	4 tumor, 2 osteomyelitis	Yes	1 (intraoperative hypotension)	1 graft failure - venous thrombosis	100%	3	16
Moran et al. ⁵¹	12	6	Thoracic, lumbar and pelvis	8 tumor, 4 osteomyelitis	Yes	1 (postoperative MI)	1 pseudarthrosis (spine case), 1 graft failure (pelvic case)	75% for spine cases	4.5	45
Wuisman et al. ²⁹	8	8	Thoracic and lumbar	4 tumor, 1 neurofibromatosis, 1 arterial vascular malformation, 1 osteoporosis, 1 osteogenesis imperfecta	Yes	1 (5 wk postoperative—cause unknown)	0	100%	4.5	31mo
Jandali et al. ⁴⁰	3	3	Pediatric cervical and thoracic	3 tumor	Yes	0	0	100%	2.8	NR
Meyers et al. ³⁹	1	1	L5-S1 grade 4 spondylolisthesis	Neuroblastoma	Yes	0	0	100%	NR	24
Moche et al. ⁵⁵	1	1	Cervical	Retropharyngeal abscess and osteomyelitis	No	0	0	100%	NR	15

Contd...

Contd...

Author	Number of patients	Number of spine patients	Anatomic location	Pathology	Prior radiation	Mortality	Complications	Fusion rate	Mean time to fusion, mo	Mean length of follow-up, mo
Freidberget al. ⁵³	1	1	Cervical	Arnold Chiari, postlaminectomy kyphosis	No	0	0	100%	4	4
Hubbard et al. ³⁸	1	1	Thoracolumbar	Post-traumatic kyphosis	No	0	0	100%	NR	48
Clemens et al. ²²	52	3	Thoracic and lumbar	Tumor	Yes	*	*	*	3.9	NR
Erdman et al. ⁴¹	4	4	Thoracic and lumbar	Osteomyelitis after prior spinal instrumentation	No	0	0	100%	NR	36
Hu et al. ³⁶	4	4	Cervical	3 tumor, 1 tuberculosis	Yes	0	1 postoperative infection require debridement	100%	NR	39
Yen et al. ³⁷	1	1	Thoracolumbar	Osteomyelitis	No	0	0	100%	NR	50

NR: Not reported.

*Not separately reported.

level.³⁹ The patient had previously undergone resection of a neuroblastoma with radiation. The patient was initially treated with a nonvascularized fibula autograft but went onto nonunion and had progression of the slip and persistent neurological complaints. Revision surgery with a vascularized fibula graft passed posteriorly from S2 to L5 was performed. This resulted in fusion and no progression of the slip at 2 years. Freidberg et al. reported on the use of a vascularized fibula graft for progressive cervical kyphosis.⁵³ The patient was 24-year-old male who had previously undergone a posterior cervical laminectomy for the treatment of an Arnold-Chiari malformation. He subsequently developed progressive kyphosis and myelopathic symptoms and had an anterior fusion from C3 to C5 without correction of the kyphosis. His symptoms continued to progress. He ultimately underwent an anterior corpectomy removing all of C3, C4, and C5 and a fusion was performed using vascularized fibula graft from C2 to C6. The patient went onto fuse and had stabilization of his neurological symptoms.

Donor Site Complications

In addition to the risk associated with these intricate spinal procedures, the use of a vascularized fibular graft has the potential for complications at the donor site as well. In the immediate perioperative phase, these potential complications include poor wound healing, infection, iatrogenic nerve or vascular injury, and compartment syndrome. Tang et al. reported a 17% incidence of wound-healing problems including 4% that required a secondary procedure.⁵⁶ They also reported a 33% incidence of iatrogenic injury. Of these the majority were minor (defined as a neuroma or sensory defect), but there was a 2% incidence of major complication (fracture, paralysis or vascular injury). Long-term complaints include pain (11.5–60%), dysesthesia (11.8–50%), subjective instability (30–42%), an inability to run (20%), and objective weakness (10–37%).^{56–58} Weakness was most commonly reported with great toe extension followed by great toe flexion, although there have been reports of weakness in other toes and in the ankle. The weakness was often minor, commonly only slightly weaker than the contralateral side (4/5) and only occasionally having some weakness relative to gravity (3/5).⁵⁷ Vail et al. suggested that sensory and pain around the ankle complaints tended to increase over time following the surgery, while any motor weakness observed at 3 months following surgery was also seen at 5-year

follow-up.⁵⁷ Gait analysis have demonstrated decreased walking preferred velocity in patient undergoing vascularized fibula graft as well as increased variation in stride time while walking at increased velocity and with increased loads.⁵⁸ These finding suggest that the normal patterns of gait are not re-established following fibular autograft; however, the impact of these gait abnormalities to the patients in their activities of daily living is thought to be minor. Late fractures of the fibula graft have also been reported in patients undergoing vascularized fibula graft performed for the treatment of defects in the extremities.^{45,54}

When performing a vascularized fibula graft in skeletally immature children, there is an additional risk of developing a valgus deformity at the ankle due to asymmetric growth between the fibula and the tibia.⁵⁹ A tibiofibular syndesmosis performed at the time of index surgery minimized the risk of valgus deformity. Omakawa et al. also reported that, if the deformity is caught early a lateral wedge osteotomy can be performed to correct it.⁵⁹ This suggests the need for regular radiographic postoperative monitoring in children undergoing this procedure.

SUMMARY

The ability of vascularized grafts to achieve fusion in even the most challenging environments has been well documented; however, the advantages of these procedures must be balanced against the high level of surgical skill required to perform them, the increased operative time and the increased risk associated with these procedures. For the majority of cases, fusion can be achieved with conventional bone grafting techniques. However, for complex cases where a high likelihood of pseudarthrosis can be anticipated, the use of vascularized bone graft can be invaluable. Most commonly, these cases involve resection of tumors with concomitant radiation treatment, infections, especially after prior failed surgical treatment, or deformity. When possible, local transfer of vascularized rib graft may be adequate. The free transfer of a vascularized fibula may be more appropriate when increased structural support is needed or in areas of the spine where local transfer is not possible. The techniques for microvascular anastomosis used to perform a vascularized fibula graft are not familiar to most spine surgeons and team approach is recommended. While the indications for vascularized bone graft in spine surgery are limited, the use of these techniques can be invaluable in the treatment of complex spine pathology.

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Bone Morphogenetic Protein and Lumbar Fusion

Bhavuk Garg, Alok D Sharan

Snapshot

- » Bone Morphogenetic Protein Structure
- » How BMP Works?
- » Physiological versus Pharmacological BMP
- » Role of BMP in Lumbar Fusion
- » Concerns with BMP use
- » Bone Morphogenetic Protein in Infection and Tumors
- » Future Approaches for BMP in Spinal Fusion

INTRODUCTION

Bone morphogenetic protein (BMP) has always remained a subject of excitement as well as controversy since 1965, when Marshall Urist¹ was able to demonstrate the osteogenic potential of demineralized bone pieces, when implanted into animals intramuscularly. He introduced the term “bone morphogenetic protein” for an active ingredient, which he postulated to be present in bone matrix, capable of differentiating pluripotent cells into osteogenic cells. Today BMP is the only unique bone growth factor known, which is capable of differentiating pluripotent cells into osteogenic cells. Thus, BMP is a mitogen as well as a morphogen.²

Reddi and Sampath later demonstrated that only the protein component of bone matrix was capable of inducing new bone formation.² Today several types of BMPs have been identified; however, FDA (Food and Drug Administration) approval has only been given for BMP-7 (OP-1, Stryker biologics, Hopkinton, MA) and BMP-2 (InFuse Bone graft, Medtronic, Memphis, TN) for human use. Urist used semipurified human BMP extract for his experiments, and one other bovine BMP extract called Ne-Osteo TM has been used in rats and nonhuman primates. Both commercial BMP preparations (BMP-2 and BMP-7) available for human use are produced through recombinant DNA synthesis technology and thus are free from risk of infection transmission or allergic reactions.²

BONE MORPHOGENETIC PROTEIN STRUCTURE

Bone morphogenetic protein belongs to the transforming growth factor-beta (TGF- β) super family, which also includes growth and differentiation factors, anti-Mullerian hormone, activin, nodal, and TGF- β s. Bone morphogenetic protein 1 is not part of this super family as it does not have the C-terminal of TGF- β . More than 47 members of BMP family have been discovered to date.²⁻³

Bone morphogenetic proteins can be divided into three groups based on their amino acid sequence. The first group contains BMP-2 and BMP-4. They differ mainly in the amino terminal sequence. The second group contains BMP-5, 6, 7 (OP-1), and 8 (OP-2). These molecules are relatively larger than the first group. The third group contains BMP-3 (osteogenin), which is quite different.^{4,5}

Human BMP comprises only 0.1% by weight of all bone protein and is most abundant in diaphyseal cortical bone. It exists in the extracellular matrix and is not accessible until the bone matrix has been demineralized.⁶ The basic structure of BMP (30–38 kDa) is in the form of two subunits, which can be identical (homodimer) or different (heterodimer). Heterodimers are difficult to prepare than homodimers, and currently available BMP preparations consists of homodimers only although heterodimeric formulation consisting of BMP2/BMP7 has been reported around 20 times more potent than homodimers.²

HOW BMP WORKS?

The hallmark of BMPs is their ability to enhance osteoinduction. The osteoinductive role of BMPs acts as both a chemotactic agent and a growth and differentiating factor.⁴ Bone morphogenetic protein is capable of stimulating the entire process of bone formation. However, Cheng et al. reported that BMP-2, 6, and 9 are more effective in inducing osteogenesis from differentiation of precursor cells than other BMPs.^{4,7}

Bone morphogenetic proteins can induce both endochondral and intramembranous bone formation depending upon its concentration, the carrier, site of implantation, and oxygen tension.^{2,8} Various cells, such as mesenchymal stem cells, osteoblasts, and osteoclasts, have specific receptors for BMP. There are two receptor types: BMPR I and II. Bone morphogenetic protein receptor I is further divided into types IA and IB. These different receptors are the reasons why different types and same types of cells with different ages respond differently to BMP.³

The binding of BMP to these receptors triggers a second messenger pathway in the cytoplasm leading to the expression of BMP response genes in the nucleus. A set of signal modulating proteins called Small “Mothers Against” Decapentaplegic (SMADs), which are present in the cytoplasm, further moderates the BMP gene transcription. This chain leads to cellular migration or chemotaxis, cellular proliferation, and their differentiation into chondrocytes or osteoblasts. Low concentration of BMP and less oxygen tension lead to endochondral bone formation, while high concentration of BMP and more oxygen tension stimulate direct intramembranous bone formation.² In addition to bone formation, BMPs have also been shown to impact the development of viscera, postnatal growth, and intervertebral disc homeostasis.^{3,8}

The bone formed as a result of BMP application is usually physiologically normal. Also, the osteoinduction and thus bone formation occur locally only without any systemic augmentation. This osteoinduction is limited temporally only to the time when the BMP is present. The action of BMP is controlled by many factors at many levels. Various soluble inhibitory proteins, such as noggin, chordin, and follistatin, inhibit the binding of BMP to receptors extracellularly. Intracellularly, the combination of signal transducing and inhibitory SMAD proteins controls the action of BMP as mentioned earlier.⁶

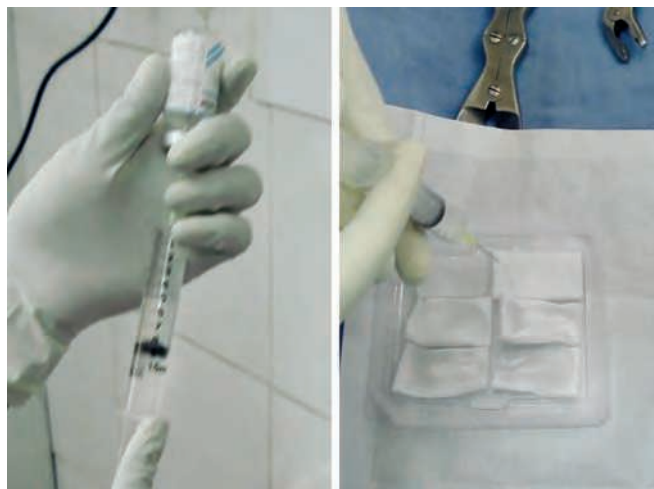


Fig. 34.1: Pharmacological bone morphogenetic protein (BMP) is first prepared in a solution form in a syringe and then sprinkled over collagen patches, which serve as a carrier for BMP.

PHYSIOLOGICAL VERSUS PHARMACOLOGICAL BMP

Bone morphogenetic protein is normally present physiologically in human bones in very small concentration and plays an active role in normal bone healing. To achieve a spinal fusion, a larger concentration of BMP is required to compensate for the diffusion of recombinant BMP from the site of application. Also, the degradation of pharmacologically applied BMP is rapid. There are some natural inhibitors of BMP in vivo like noggin and chordin, which attenuate the action of pharmacologically applied BMP.²

Pharmacological Recombinant Human (rhBMPs) are soluble factors and tend to diffuse away from the fusion site when used alone. Therefore, these factors are combined with a carrier that serves to contain the BMPs and release them gradually (Fig. 34.1). These carriers may also act as osteoconductive scaffolds.^{6,9} Various other carriers of rhBMP-2 include organic carriers such as polylactic acid polymer, collagen, demineralized bone matrix, autograft, and noncollagenous protein carriers, and inorganic carriers like hydroxyapatite-tricalcium phosphate (HA-TCP); true bone ceramic made from sintered bovine bone have been tested in various animal studies and have been found useful.^{2,10-12}

ROLE OF BMP IN LUMBAR FUSION

Spinal fusion is a commonly done procedure across the world to stabilize the spine for various disorders, since

Albee¹³ first described it in 1911. Approximately 250,000 bone graft procedures are performed each year for spinal fusion, and bone graft is the second most common human tissue to be transplanted. Associated donor site morbidity and the limited amount of bone graft have always led to the search for an ideal alternative. Allografts, bone substitutes, and growth factors have been used; however, each has its own merits and demerits.⁴

Various animal and human studies have shown that pharmacological application of BMP is an efficient mean to enhance or achieve spinal fusion. Most of the studies involve the use of rhBMP-2, while rhBMP-7 (OP-1, Stryker biologics, Hopkinton, MA) has recently been cleared for humanitarian device exemption “as an autograft alternative in compromised patients requiring revision posterolateral lumbar fusion, for which autologous bone and bone marrow harvest are not feasible or are not expected to promote fusion.”²

Boden et al. studied the role of rhBMP-2/HA-TCP in posterolateral lumbar fusion following laminectomy in nonhuman primates and found a dose-dependent increase in the amount as well as quality of bone with rhBMP-2.¹⁰ Bone morphogenetic protein has also been reported to surmount the negative effect of nonsteroidal anti-inflammatory drugs, chemotherapy, and nicotine in various studies.^{2,14-16} rhBMP-2 has even been shown to increase the volume as well as maturity of spinal fusion mass, when added to autograft.²

Boden et al.¹⁷ showed higher rates of new bone formation in the nonhuman primate model undergoing intertransverse fusion when rhBMP-2 was added to decorticated bone. Sandhu et al.¹⁸ reported that intertransverse fusion was obtained with rhBMP-2 without decortication.

In 2000, Boden et al.¹⁹ published the results of a prospective, randomized controlled, human clinical pilot trial to determine the feasibility of using rhBMP-2/collagen as a substitute for autogenous bone graft inside interbody fusion cages used in Anterior Lumbar Interbody Fusion (ALIF) surgery to achieve arthrodesis in humans. However, the sample size ($n = 14$) was very small. The arthrodesis was found to occur more reliably in patients treated with rhBMP-2-filled fusion cages than in controls treated with autogenous bone graft. There were no adverse events related to the rhBMP-2 treatment. Serology analysis did not show any increased BMP antibodies titer in patients treated with rhBMP-2. This study was one of the first to show consistent and unequivocal osteoinduction by recombinant growth factor in humans.

In 2002, Burkus et al.²⁰ published the results of a multicenter prospective, randomized, nonblinded, 2-year study involving 279 patients undergoing anterior lumbar interbody fusion for degenerative lumbar disc disease, and reported better fusion rates with rhBMP-2 as compared to autogenous iliac crest bone graft. There were more complications in the bone graft group. In 2002, the FDA approved the use of rhBMP-2 on an absorbable collagen sponge, when placed inside the fusion cage as an autograft substitute for anterior lumbar interbody fusion.^{2,8} However, various surgeons have used it for various off-label indications as well.

Alexander et al.²¹ used the rhBMP-2 with posterior lumbar interbody fusion and reported slower fusion rates in BMP group. They also found new bone formation along the insertion track of cages, however without any neurological deficit. In view of potential harmful effect, they stopped this study.^{4,21}

Boden et al.²² used a ceramic carrier instead of a collagen sponge and used a total of 20 mg rhBMP-2 per side (2.0 mg/mL concentration) for posterolateral fusion in humans and achieved 100% fusion rate for BMP-2 as compared to 40% fusion rate in autograft alone. Glassman et al.²³ conducted a prospective randomized nonblinded study of iliac crest bone graft versus rhBMP-2/compression-resistant ceramic matrix composite. They used a total of 40 mg rhBMP-2 (20 mg on each side) in a concentration of 2.0 mg/mL in 10 mL of ceramic matrix and found statistically higher fusion grades in rhBMP-2 group as compared to autograft at 6 months as well as 12 months follow-up.

In a recent report by Gerszten et al.,²⁴ clinical outcomes were similar for patients who underwent an AxiaLIF L5-S1 interbody fusion with or without rhBMP-2. Their data suggested that there is no statistically significant difference on fusion rates when using rhBMP-2.

Clinical results of rhBMP-7 are less promising as compared to rhBMP-2. Vaccaro et al.²⁵ conducted a prospective, randomized, controlled, multicenter clinical pilot study comparing the rhBMP-7 (OP-1) with autogenous iliac crest bone graft. They reported that rates of radiographic fusion, clinical improvement, and overall success associated with the use of OP-1 were at least comparable to that of the autograft controls for at least 48 months after surgery. They also suggested rhBMP-7 as a viable bone graft alternative for spinal fusion.

A recent published review of the Nationwide Inpatient Sample from 2002 to 2008 studied the impact of BMPs on frequency of revision surgery, use of autograft bone, and

total hospital charges in surgery for lumbar degenerative disease. The assessment found 46,452 patients from 2002 to 2008 undergoing thoracolumbar or lumbar arthrodesis procedures for degenerative disease. There was a steady growth in lumbar spine fusion and in the use of BMP. The use of BMP increased from 2002 to 2008. Revision procedures decreased over the study period. The use of autograft decreased substantially after the introduction of BMP but then returned to baseline levels; there was no net change in autograft use from 2002 to 2008. Use of BMP correlated with substantial increase in hospital charges.²⁶

Crandall et al.²⁷ published the results of a retrospective review of prospectively collected data of a large series. A total of 509 consecutive adults underwent open posterior instrumented fusion, augmented with Transforaminal Lumbar Interbody Fusion (TLIF) at 872 levels using a cage and rhBMP-2, with minimum 2-year follow-up. Cohort diagnoses included 179 degenerative, 207 spondylolisthesis, and 123 deformity patients. The efficacy of TLIF with BMP is supported in this large series with long-term follow-up, independent of industry. Reliable fusion and improved outcomes can be expected in adults undergoing TLIF for deformity, spondylolisthesis, and degenerative disease. Most complications occurred in patients with deformity.

CONCERNS WITH BMP USE

Although the FDA has approved BMP for some selected indications, spine surgeons have been commonly using them for off-label indications. Unfortunately, the off-label use of BMP is occurring more often than approved indications (Fig. 34.2). This has led to the emergence of various adverse effects associated with BMP use. Various commonly reported adverse effects when rhBMP-2 has been used in posterior lumbar interbody fusion include local bone resorption,²⁸⁻³⁰ postoperative radiculitis,³⁰⁻³³ endplate osteolysis with interbody device subsidence, and ectopic bone formation.^{34,35}

Various *in vitro* studies have suggested a notable host inflammatory response as the mechanism of action by which rhBMP-2 augments spine fusion.³⁴ As the pharmacological dose of rhBMP-2 is about 1 million fold more than the physiologic concentration, a possibility of potent local inflammatory response exists.^{34,36} Reported complications such as soft tissue swelling, hematoma formation, cyst formation, and vertebral body resorption demonstrate a host reaction associated with the use of rhBMP-2 in the spine.³⁴ Taher et al.³⁷ recently reported a serous contralateral psoas muscle fluid accumulation after BMP-2

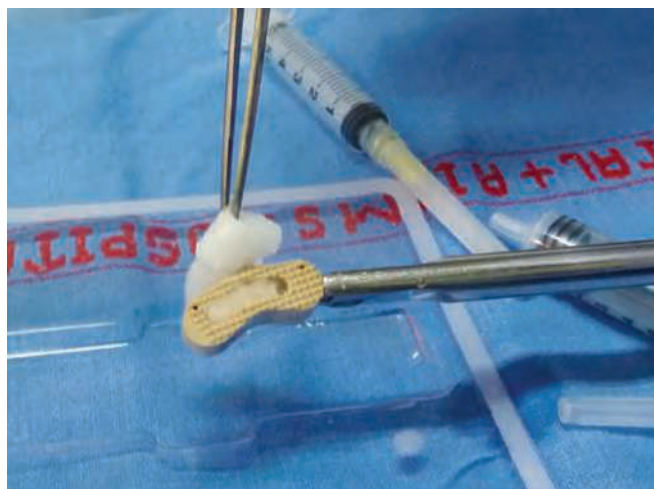


Fig. 34.2: Off-label use of bone morphogenetic protein (BMP) is much more common than approved indications. In this case, BMP is used inside a banana cage for TLIF, which is not approved by FDA.

implantation for lateral lumbar interbody fusion. Merrick et al.³⁸ reported a case of “acute epidural lipedema,” rapid accumulation of edematous adipose tissue causing cauda equina syndrome after a lumbar decompression and fusion surgery using rhBMP-2. They also cited an intense inflammatory reaction as a reason for this.

Another potential complication inherent to BMP use has been the ectopic bone formation. Various factors,³⁴ such as position of the interbody cage in relation to the posterior margin of vertebral body,^{39,40} amount of BMP,^{33,41} carrier of BMP,³³ and the absence of a posterior barrier confining BMP to the interbody space³³ have been linked to ectopic bone formation. Mannion et al. used a relatively low dose of BMP with minimally invasive lumbar interbody fusion; however, they still reported the same complications.⁴²

Containment of rhBMP-2 and associated inflammatory reaction seems to be most important to limit the complications.³⁴ Intact posterior annulus and posterior longitudinal ligament appear to be protective of this reaction occurring in anterior lumbar interbody fusion surgery.⁴³ Posterior interbody techniques allow access of rhBMP-2 to the epidural space and neural elements as the posterior annulus is removed. Various barrier techniques have been described including the placement of one sponge against the anterior annulus followed by placement of local autograft or allograft behind the sponge, followed by the allograft strut, and completing the barrier with morselized cancellous allograft posterior to the strut.⁴⁴ The use of fibrin glue⁴⁵ has shown an effective method of limiting diffusion and ectopic bone formation.

Besides this, adequate hemostasis is essential to avoid the absorption of BMP by a hematoma at the decompression site. It is not advisable to leave collagen-based hemostatic agents, where decompression has been performed, in contact with the BMP implant, because BMP may elute from its collagen carrier into the collagenous hemostatic agent and thus enter the region of decompression. Leakage of rhBMP-2 or OP-1 outside the fusion area may lead to adjacent-level fusion.⁶

Even with on-label indication of BMP use for ALIF, several studies have reported higher rates of retrograde ejaculation (RE) with BMP use. This effect may be associated with an increased risk of postoperative urinary retention after BMP-2 exposure. The magnitude of the RE effect may be increased with concomitant prostatic disease treatments.⁴⁶⁻⁴⁸ Comer et al.⁴⁸ also suggested that RE rate may be decreased by careful handling of the BMP-2 around anterior spinal structures.

Carragee et al. reported eight new malignancies in the rhBMP-2 group and only two in the Iliac Crest Bone Graft (ICBG) group ($p = 0.1$) in a randomized controlled trial.^{49,50} Lad et al.⁵¹ reported the results of a large, independent, propensity-matched study ($n = 4,698$) and suggested that the use of BMP in lumbar fusions is associated with a significantly higher rate of benign neoplasms, but not malignancies.

Very recently, the YODA (Yale University Open Data Access Project) report was completed and published.⁵² They found that after a systematic evaluation and synthesis of all available evidence, both systematic reviews published independently concluded that rhBMP-2, compared with iliac crest bone grafting, does not improve pain or function and increases adverse events, possibly including cancer.

BONE MORPHOGENETIC PROTEIN IN INFECTION AND TUMORS

Although the use of rhBMP-2 in the presence of infection and tumor represents contraindications outlined by its manufacturers,⁵³ there have been published reports describing the use of BMP in these indications. Allen et al.⁵⁴ published a case series of 21 patients with vertebral osteomyelitis in whom they used rhBMP-2 in an off-label manner along with an anterior structural allograft or titanium cage and posterior instrumentation and fusion with iliac crest autograft.

FUTURE APPROACHES FOR BMP IN SPINAL FUSION

Many experimental approaches involving gene therapy are being investigated to expand the role of BMP in spinal fusion. These approaches involve the delivery of complementary DNA encoding BMP gene, using various vectors for BMP gene delivery, or in vitro transduction of cells with BMP gene, followed by implantation of these cells into the host. Postulated advantages of this gene therapy include more prolonged and physiological BMP production rather than a large single bolus pharmacological dose.²

A new protein called LIM mineralization protein-1 (LMP-1) has also been studied, which is an intracellular protein and is thought to induce osteoinduction. Osteoinductive properties of LMP-1 involve the synthesis of several BMPs and the recruitment of host cells that differentiate and participate in direct membranous bone formation.⁵⁵

Gene therapy has opened a new frontier for the role of BMP in spinal fusion; however, it is a double-edged sword and has potential risks in the form of neoplasms, infections, and immune responses to the viral vectors leading to immune reaction, toxicity, or organ failure. A continued and improved understanding of BMP in spinal fusion will help to circumvent these issues and will bring cost-effective as well as safe strategies to optimize the use of BMP in lumbar fusion.

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SECTION

5

Cervical Spine

Brian W Su



Standard and Extended Transoral Approaches to the Upper Cervical Spine

Morio Matsumoto

Snapshot

- » Standard Transoral Approach
- » Extended Transoral Approach

- » Complications

INTRODUCTION

The craniovertebral junction (CVJ) and upper cervical spine are occasionally involved in cases of tumor, inflammatory disease (such as rheumatoid arthritis (RA) and pseudotumor), and congenital disease. Patients with clinical symptoms including pain and neurological deficits due to these diseases need decompression and fusion surgery, and those with locally aggressive tumors require tumor resection combined with reconstruction.

There are several possible surgical approaches to lesions in the CVJ and upper cervical spine including posterior, posterolateral, anterolateral, and anterior. Regardless of the approach, the complex anatomy of the upper cervical region, which includes the cranial nerves and carotid vessels, makes surgery of the CVJ and upper cervical spine technically demanding.

Of these approaches, the transoral anterior route is a very straightforward way to reach the CVJ and the upper cervical spine. This is largely because there are no critical anatomic structures, such as cranial nerves or carotid arteries, in the midline. Transoral approaches can be divided into standard and extended approaches. The standard approach is not accompanied by an osteotomy of the maxilla or mandible, while the extended approach requires an osteotomy of these structures to create a wider surgical field.

The transoral approach was first described by Kanavel¹ as the simplest and most commonly used approach for ventro-medial extradural lesions of the CVJ. It was

popularized by Fang et al.² for the treatment of atlantoaxial lesions such as dislocation and tuberculosis. Later, Menzes et al.^{3,4} and Crockard et al.^{5,6} separately reported successful anterior decompression of the upper cervical spine using this approach.

The extended approach has been used in the otorhynolaryngeal area for the resection of tumors in the pharynx and tongue.⁷⁻¹⁰ The first use of this approach for spinal surgery was reported by Hall et al.¹¹ for the treatment of myelopathy due to fixed cervical kyphosis in the upper cervical spine. This approach is frequently chosen for the treatment of primary malignant tumors in the upper cervical spine that require aggressive resection, including chordoma, giant cell tumor, and chondrosarcoma.¹²⁻¹⁸

STANDARD TRANSORAL APPROACH

Indications

This approach is indicated for lesions in the ventral upper cervical spine, including irreducible atlantoaxial subluxations when the odontoid peg compresses the medulla and spinal cord, rheumatoid pannus, pseudotumor, congenital anomalies with craniocervical settling, fixed atlantoaxial rotatory fixation, pyogenic spondylitis, tuberculosis, and intra- and extradural tumors.

Using this approach, the odontoid process can be resected, and the medulla and spinal cord can be decompressed.^{5,6,19} Pyogenic and tuberculous spondylitis at C1-2 can be debrided followed by anterior atlantoaxial arthro-

desis through this approach or by posterior occipitocervical fusion.²⁰ This approach is also used to biopsy lesions in the upper cervical spine.²¹ For primary malignant tumors such as a chordoma that requires total surgical resection, an extended approach is often necessary. In addition, for patients with limited oral opening, as is often seen in cases of RA, an osteotomy of the mandible and/or maxilla may be necessary.

Recent advances in posterior instrumentation surgery, including pedicle screws, transarticular screws, and lateral mass screws, have gradually obviated the need for the transoral approach. Rigid posterior instrumentation permits indirect decompression by reducing cranial settling²² and atlantoaxial subluxation. Spontaneously regressed pannus or pseudotumor can often be treated by the posterior approach alone as well.²³

Surgical Anatomy

The retropharyngeal wall is composed of the mucosa, buccopharyngeal fascia, constrictor muscles, prevertebral fascia, and prevertebral muscles (longus capitis and longus coli). The anterior longitudinal ligament covers the vertebrae. Usually, the anterior tubercle of C1 can be palpated easily from the mouth, at the midpoint.

The atlanto-occipital membrane connects the foramen magnum with the anterior arch of the atlas, and the apical ligament is attached to the apex of the odontoid process. The atlantoaxial joint can be reached bilaterally by retracting the flap of the mucosa, the prevertebral muscles, and the fascia laterally. The odontoid process can be found after the resection of the anterior arch of C1, and the transverse ligament lies behind the odontoid process.

Preoperative Preparation

Comprehensive radiographic work-up includes magnetic resonance imaging (MRI) and computed tomography (CT) scans. A CT angiogram of the cervical spine is recommended to look for abnormality of the vertebral arteries, which often occurs in patients with congenital anomalies and RA.

Hygiene of the oral cavity is important to prevent postoperative infection. Patients are encouraged to wash their mouth using a povidone-iodine solution. They should be referred to a dentist to check, if they have dental caries, which must be treated before surgery. Broad-spectrum antibiotics that will cover anaerobic bacteria should be administered prior to surgery.^{7,24}

For patients with tumors, pannus, pseudotumor, or with cranial settling of the odontoid process due to RA or a congenital anomaly, posterior stabilization with or without reduction of the basilar invagination should be performed

prior to the anterior procedure. Postoperatively, anesthesia must be consulted for postoperative respiratory management and otorhinolaryngologists should be asked to assess the retropharyngeal wound.

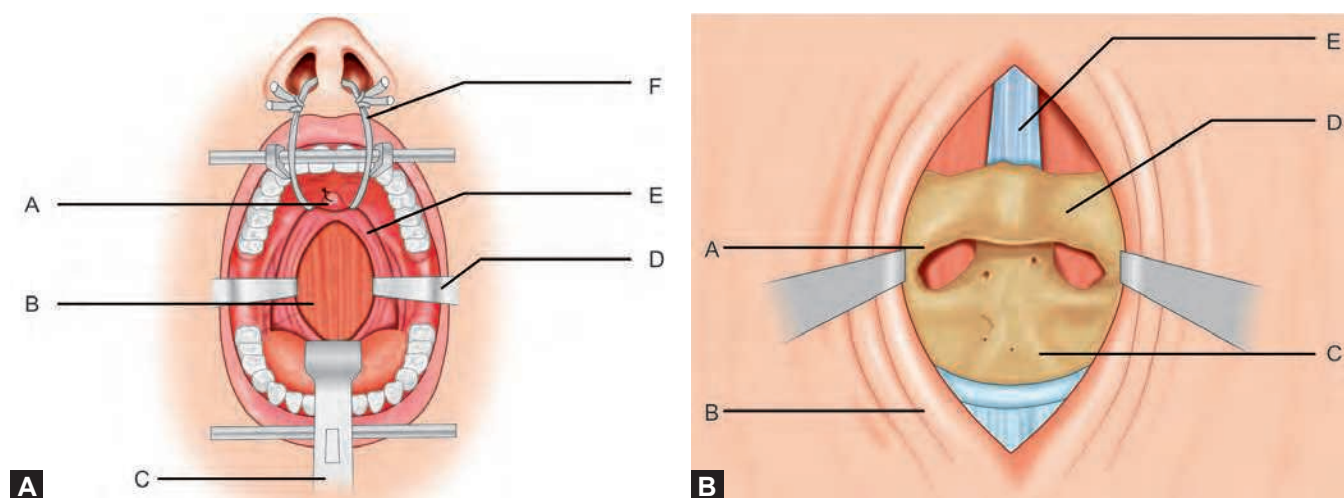
Surgical Technique

The patient is placed supine on the operating table. The skin is disinfected with povidone-iodine solution and the oral cavity with benzethonium chloride or chlorhexidine gluconate solution. Transoral intubation is conducted, and an endotracheal tube is placed. The authors prefer the RAE endotracheal tube, which goes underneath the tongue retractor, so it does not interfere with the surgical procedure. Alternatively, the tube can be placed at either corner of the mouth. If necessary, a central line is placed for hemodynamic monitoring during surgery and for postoperative total parenteral nutrition. To achieve good visualization of the retropharyngeal surgical field, the uvula and soft palate are lifted up using Nelaton's soft catheters, which are passed through the nostril on each side, pulled out through the mouth, and clipped using Kocher clamps under light tension.

After draping, a self-retaining oral retractor is placed and the mouth is kept open. The tongue retractor is attached and the tongue is pressed down to allow for a wide surgical view (Fig. 35.1A).²⁵ The retractor needs to be released every 30–40 minutes to prevent ischemia and congestion of the tongue. A stay suture is placed in the uvula, which is shifted away from the midline. If the lower end of the clivus needs to be visualized, the soft palate is divided at the midline.

The procedures used to increase the surgical field described below must be performed under good illumination, using a surgical microscope. More recently, transoral or transnasal endoscopy has been used for visualization of the occipitocervical junction, thereby minimizing surgical invasiveness and palate dissection.²⁶

After infiltration of 0.5–1% lidocaine and 1/1–200,000 epinephrine, the retropharyngeal wall (i.e. the mucosa and muscles) is incised at the midline using a knife. The anterior tubercle of C1 can be palpated and serves as a landmark for the incision. Caution should be used to accommodate for C1 rotation. Using electro cautery the prevertebral muscles, such as the longus colli and longus capitis, and the anterior longitudinal ligament are then divided and separated from C1 and C2. The mucosa and muscles are then retracted bilaterally using deep self-retaining Crockard retractors (Fig. 35.1B). Usually, this approach allows visualization of the tip of the odontoid process and the lower portion of the clivus cranially, the bilateral anterior atlantoaxial joints laterally, and the C2 vertebral body and the upper part of the C3 vertebral body caudally.²⁷



Figs. 35.1A and B: Schematic drawings of the standard transoral approach. (A) After incision of the retropharyngeal mucosa and constrictor muscles. A, uvula; B, retropharyngeal wall; C, tongue retractor; D, Longus Colli muscles; E, retropharyngeal mucosa and constrictor muscles; F, Nelaton's soft catheters. (B) After incision of the anterior longitudinal ligament and periosteum. A, lateral atlantoaxial joint; B, retropharyngeal mucosa and constrictor muscles; C, C2 vertebral body; D, anterior arch of C1; E, anterior atlanto-occipital membrane. *Source:* Reprinted with permission from Matsumoto M. Anterior decompression of upper cervical spine. In: Toyama Y (Ed). Integrated Handbook of Orthopaedics, Vol. 6. Nakayama Shoten Co, Ltd, Tokyo; 2009. pp. 114-18 (in Japanese).

The anterior arch of C1 can be easily resected using an air drill and Kerrison rongeur, which then permits visualization of the odontoid process. If the odontoid process is compressing the brain stem or spinal cord, it can be resected through this approach. Thereafter, any pannus and pseudo-tumor located behind the odontoid process can be resected in the same approach.

The bilateral anterior atlantoaxial joints also can be exposed after the dissection of periosteum and joint capsules laterally. Release of the joints in patients with irreducible atlantoaxial subluxation or fixed rotatory fixation can be performed using an air drill and Penfield dissectors. Care must be taken because lateral exposure of the atlantoaxial joints may endanger the vertebral arteries.²⁴

Anterior atlantoaxial arthrodesis can be performed by curettage of the anterior atlantoaxial joint cartilage and autologous bone graft, as described by Fang.²

Recently, some authors reported the use of an anterior screw and plate system to stabilize the atlantoaxial joint.²⁸

For the closure, each layer of the retropharyngeal mucosa and muscle is meticulously approximated, with absorbable 3-0 Vicryl sutures.

Postoperative Management

Patients are kept in the intensive care unit (ICU) on a ventilator overnight or for a couple of days, until the risk for airway obstruction due to retropharyngeal edema is reduced. The decision about when to extubate the patient

should be left up to the anesthesiologist. Oral feeding with clear fluid can be started several days after surgery, followed by soft food, if appropriate.

If a patient has atlantoaxial instability after the anterior procedure, posterior stabilization using instrumentation should be performed. If the posterior procedure is going to be staged, the patient should be placed in a Halo brace or kept in bed under traction while waiting for the surgery.

EXTENDED TRANSORAL APPROACH

The extended transoral approach can be accomplished by mandibulotomy (mandible-splitting), labiomandibuloglossotomy, and palatotomies. The addition of maxillotomy, including a Le Fort I osteotomy with or without palatotomy, allows for more vertical and axial extension of the surgical field, uncovering the whole clivus.⁸ Splitting of the soft palate is usually sufficient to visualize the lower end of the clivus, and tumors of the upper cervical spine can usually be resected without maxillotomy.

Youssef et al. conducted a cadaveric study in which they demonstrated the exposure achieved by using the transoral approach and its extended modifications.^{8,29} The standard transoral approach allows visualization of the clivus to the C2 body. A mandibulotomy visualizes the clivus to C3, and a labiomandibuloglossotomy visualizes the clivus to C4 and below.^{8,27,29} Surgeons should choose the surgical approach based on the extent of the tumor as demonstrated by preoperative MRI and CT.

Preoperative Preparation

Preoperative planning for the extended approach requires several additional preparations. Consultation with oral/maxillofacial surgeons and/or otorhinolaryngologists for help with mandible and tongue splitting and reconstruction is mandatory. Radiographic evaluation of the mandible including panoramic tomography should be performed.

Usually, extensive tumor resection at the upper cervical spine results in a loss of stability of the CVJ, and posterior occipitocervical fixation prior to the anterior approach is necessary. Finally, prior to surgery, tracheostomy should be conducted for intraoperative and postoperative respiratory control (Fig. 35.2A).

Surgical Approach

Preparation of the surgical field is the same as for the standard approach.

Mandible Splitting

Mandible splitting is usually conducted by oral maxillofacial surgeons. The lower lip is incised at the midline or it can be preserved and pressed down after the mandible is split. The authors prefer the latter for the isolated mandible splitting approach, because the cosmetic outcome is better.^{30,31}

The gingival and oral mucosa and the muscles attached to the mandible are stripped off, and the mandible is split in the midline between the central incisors using an oscillating saw and a chisel (Fig. 35.2B). The halves of the mandible are separated laterally using a spreader, and the tongue is depressed between them (Fig. 35.2C). Midline incision of the soft palate can be added to expose the lower portion of the clivus. This procedure allows for visualization of the retropharyngeal space from the clivus to C3 (Fig. 35.2D).

After incision of the retropharyngeal wall, a tumor at the upper cervical spine can be resected either en bloc or piecemeal. Successful en bloc resection of a chordoma was reported by Rhine et al.³² En bloc resection is technically very demanding because of the anatomy of the upper cervical spine, and piecemeal resection using a Cavitron ultrasonic surgical aspirator, airdrill, curettes, and rongeurs is more typical.

After the completion of tumor resection, anterior reconstruction between the clivus or C1 and C4 (or below) is performed using autologous iliac crest, fibula, or a titanium mesh cage.³³ The retropharyngeal wall is then meticulously closed in layers using absorbable 3-0 Vicryl sutures. If a

primary closure is not possible due to a large defect, the retropharyngeal wall should be reconstructed using a free or pedicle muscular flap. The two sides of the split mandible are then approximated using a titanium plate and screws by the oral surgeons (Fig. 35.2E).

An illustrative case of a patient with a C2 giant cell tumor treated by the extended transoral approach is illustrated in Figures 35.3 to 35.5. The patient is a 24-year-old female with progressive quadriparesis secondary to a giant cell tumor. She underwent a staged procedure to resect the tumor and stabilize her spine. One month later, the autologous iliac crest strut became dislodged. She underwent an additional surgery, and at 5-year follow-up, she was disease free and solid bony fusion had been obtained.

Mandibuloglossotomy

A mandibuloglossotomy requires elongation of the labium incision to the submental area. Following mandible splitting, the tongue is incised at the midline using electric cautery to preserve the nerves and vessels supplying the tongue. Figures 35.6 and 35.7 depict an illustrative case of a 62-year-old female patient with a recurrent chordoma at C2. The entire floor of the mouth was divided at the midline using a sharp scalpel (Figs. 35.7A and B). After meticulous hemostasis, self-retaining retractors were placed to separate the split halves of the mandible and tongue away from the midline while pushing the soft hypoglossal tissues down (Fig. 35.7C). In this case, the lower cervical spine needed to be visualized, so the incision was extended caudally along the sternocleidomastoid muscle (Fig. 35.7D). Alternatively, DeMonte et al. reported a circumglossal approach instead of the midline approach,³⁴ and Neo et al. reported the successful resection of a chordoma at C1 using a navigation system.³⁵

After the tumor resection is complete, the retropharyngeal wall is repaired as described above, and the tongue is sutured meticulously by oral surgeons or otorhinolaryngologists. Interestingly, dysfunction of the tongue after this procedure has been reported to be rare.

Postoperative Course

These patients require extended ICU stays until their respiratory condition can be stabilized. Total parenteral nutrition or tube feeding needs to be continued for several weeks until the patient can swallow without difficulty. Therapy for dysphasia should be actively conducted, and the condition of the retropharyngeal wall and swallowing function should be evaluated before the start of oral feeding.

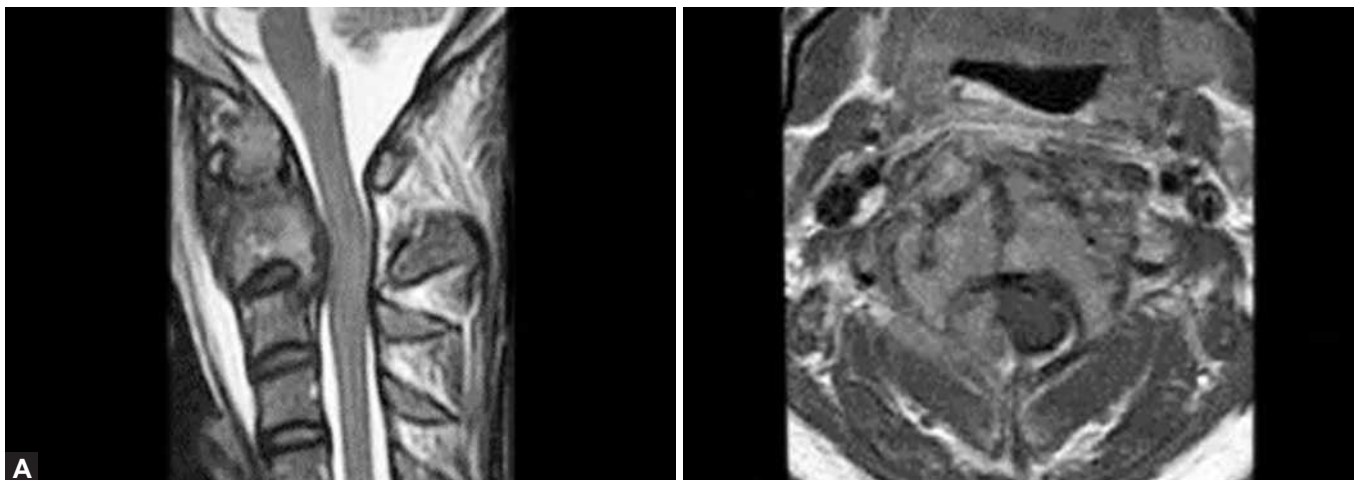
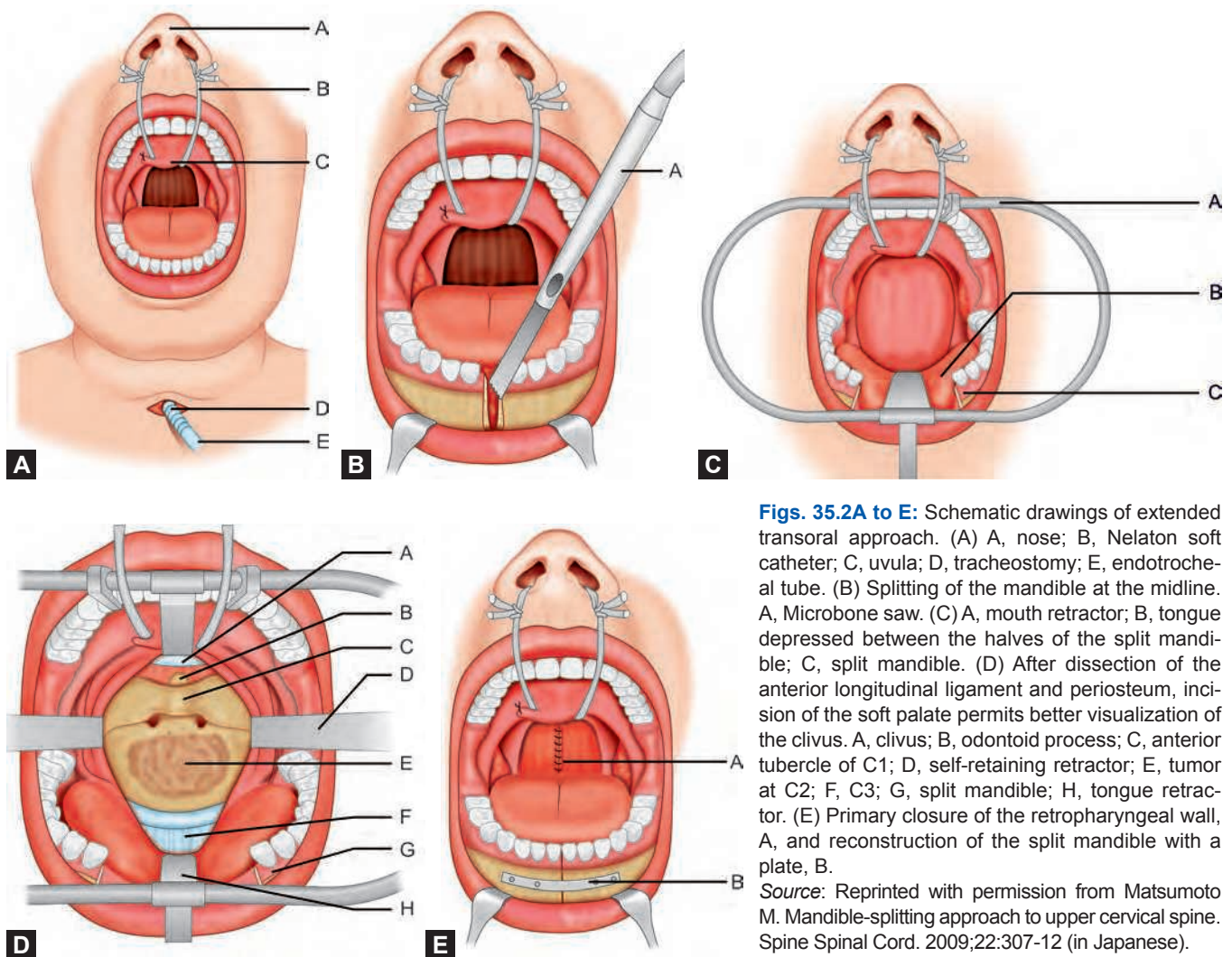
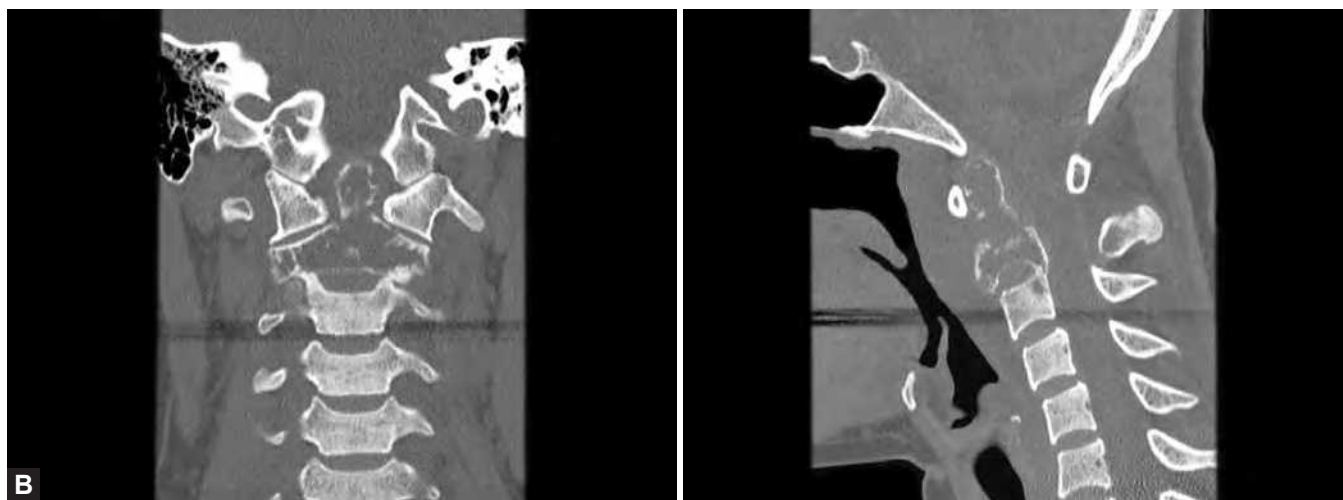
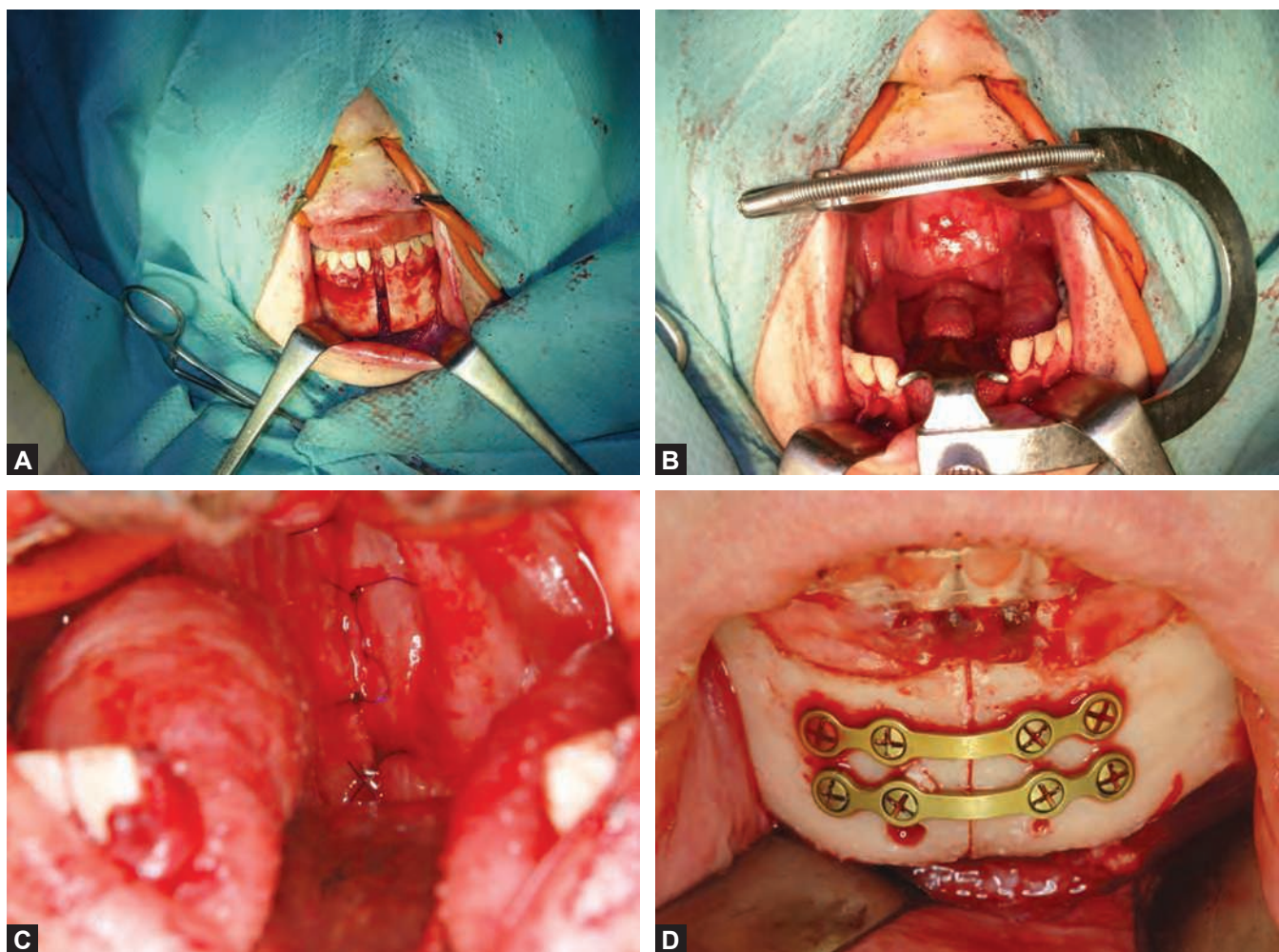


Fig. 35.3A



Figs. 35.3A and B: Preoperative radiographic findings for a 24-year-old female patient with a C2 giant cell tumor. (A) magnetic resonance imaging T2 sagittal image and Gd-enhanced axial image. (B) Coronal and sagittal reconstructed CT images.



Figs. 35.4A to D



Figs. 35.4A to E: Intraoperative photographs for the patient in Figure 35.3. (A) Splitting of the mandible. (B) Tongue depressed between the split mandible halves. (C) Primary suture of the retropharyngeal wall after tumor resection. (D) Reconstruction of the split mandible with plates. (E) Primary suture of the gingiva.

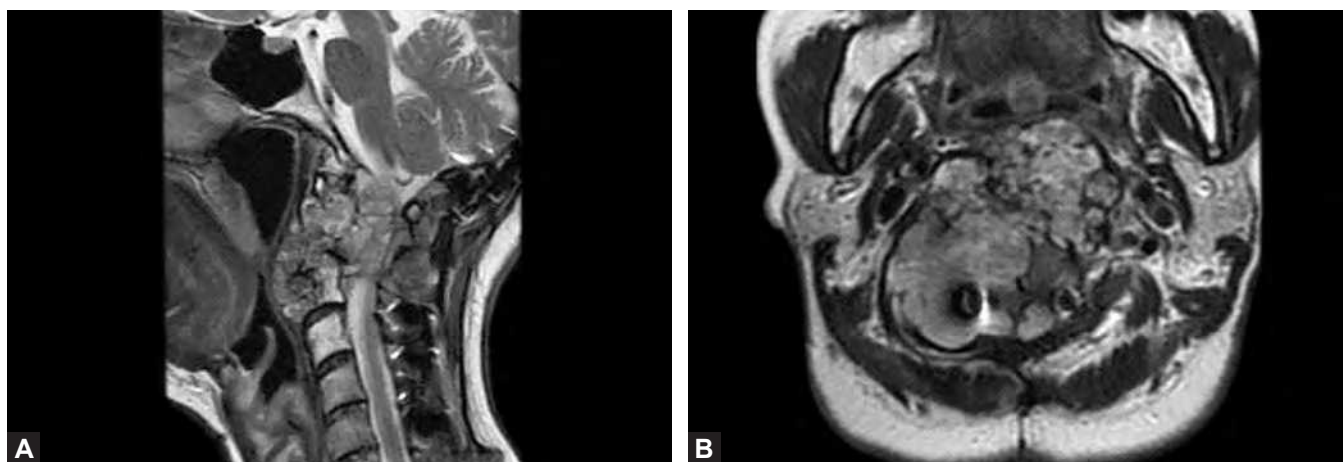


Figs. 35.5A to C: Postoperative radiographic findings for the same patient as in Figures 35.3 and 35.4. (A) Dislodgement of an autologous iliac crest strut 1 month after surgery. (B) Radiograph at final, 5-year follow-up. (C) T2-weighted magnetic resonance imaging at the final follow-up demonstrating no recurrence.

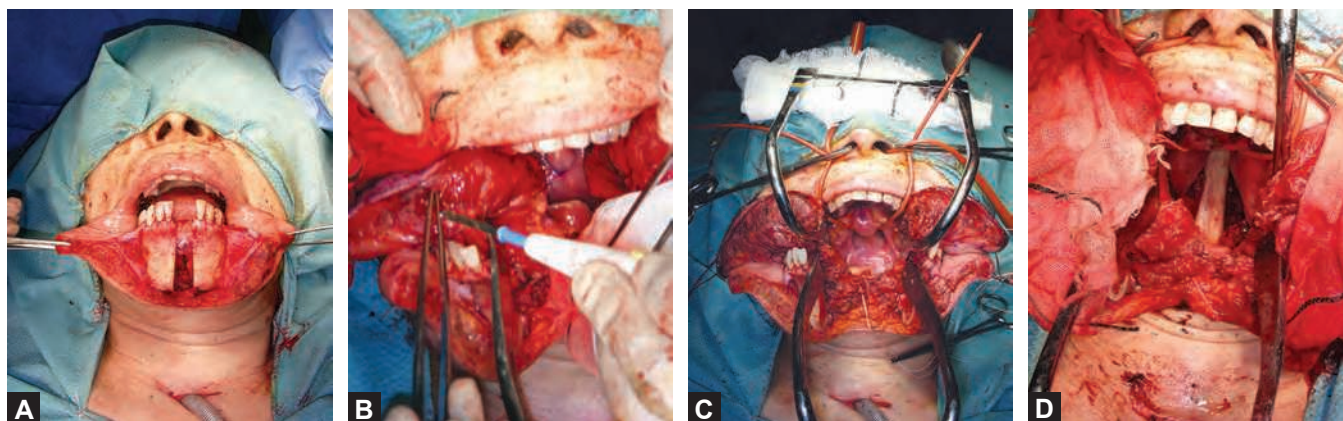
COMPLICATIONS

The transoral approach, especially an extended one, is frequently associated with complications such as prolonged dysphagia and/or hoarseness, infection, dehiscence of the

retropharyngeal wall, leakage of cerebrospinal fluid, meningitis, dislodgement of graft, and occlusal disharmony. The risk of these complications may be higher in patients who have undergone radiation therapy. Matsumoto et al. reported significant complications in three patients follow-



Figs. 35.6A and B: Preoperative Gd-enhanced magnetic resonance imaging for a 62-year-old female patient with recurrent chordoma at C2.



Figs. 35.7A to D: Intraoperative photographs for the same patient as in Figure 35.6. (A) Labium and mandible were divided in the midline. (B) Tongue was divided at the midline using an electric cautery. (C) After placement of the retractors, the retropharyngeal space was easily examined visually. (D) An autologous fibula strut placed from the clivus to C4 after tumor resection.

ing the extended transoral approach who were previously radiated.³⁶

Several steps can be taken to reduce the risk of complications. Meticulous repair of the retropharyngeal wall by primary sutures or primary muscle flaps is essential. Pre- and postoperative use of wide-spectrum antibiotics is also important to prevent infection. Fine suture of the dura in cases of incidental dural tear or durotomy for intradural tumors is indispensable to prevent cerebrospinal fluid leakage and subsequent meningitis. Subarachnoid drainage should be considered, if tight closure of the dura is not possible. Aggressive postoperative swallowing training should be encouraged to prevent prolonged dysphagia. Finally, dislodgement of a graft or cage can pose a significant problem (*see* Fig. 35.5A). The graft bed should be meticulously prepared, and the CVJ should be stabilized by the placement of rigid posterior instrumentation.

KEY POINTS

- The transoral anterior approach is a very straightforward way to reach the CVJ and the upper cervical spine. There are no critical anatomic structures, such as cranial nerves or carotid arteries, in the midline.
- The standard transoral approach is indicated for lesions in the ventral upper cervical spine including irreducible atlantoaxial subluxation, RA-associated pannus, pseudotumor, congenital anomaly with craniocervical settling, fixed atlantoaxial rotatory fixation, pyogenic spondylitis, tuberculosis, and intra- and extradural tumors with limited extension.
- The extended transoral approach is performed with an osteotomy of the mandible and/or maxilla followed by glossotomy, if necessary.
- The extended transoral approach is indicated for malignant or aggressive tumors at the craniocervical junction

that require total resection, including chordoma, giant cell tumor, and chondrosarcoma.

- The extended transoral approach should be carried out by multidisciplinary surgical teams.

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Anterior Cervical Approaches

Dennis Q Chen, Brian C Werner, Adam L Shimer

Snapshot

- » History
- » Anatomy and Landmarks
- » Anterolateral Approach (Smith-Robinson)
- » Anatomic Considerations as Related to Complications
- » Lateral Retropharyngeal (Whitesides)
- » Complications

INTRODUCTION

The anterior approach to the cervical spine is an extremely practical and elegant approach to surgically address pathologies that arise primarily from the anterior spinal column.¹ The approach chosen depends on a number of factors, including the target spinal segments requiring exposure, the nature of the procedure to be performed, anatomical considerations including deformity, and the patient's body habitus. Additionally, anterior cervical approaches can complement posterior approaches to allow surgeons to achieve circumferential surgical objectives without compromise.

HISTORY

The anterior approach to the cervical spine was described as early as the nineteenth century.² At the beginning of the last century, surgeons were mainly involved with the treatment of complications of Pott's disease, namely deformity and drainage of abscesses, and later with management of neoplastic invasion and iatrogenic instability of the cervical spine after laminectomy procedures.³ As early as 1917, Henderson argued that posterior fusion was an ineffective procedure for cervical spine tuberculosis because it did not directly address the diseased anatomy.⁴ The need for more effective treatment options for Pott's disease of the cervical spine prompted

surgeons to investigate various anterior approaches to the cervical spine over the ensuing decades.⁵⁻⁸ In one of the earliest descriptions of modern anterior cervical fusion, Bailey and Badgely note that LC Abbot described the first use of an anterior cervical fusion for a lytic lesion of C4 and C5.⁹ Advances in anesthetic techniques, the ease of the approach, and its effectiveness in managing cervical spine lesions including fractures, neoplasms, and infections led to a rapid increase in the popularity of the anterior cervical surgical approach. The technique was extended to cervical degenerative disc disease by Robinson and Smith and Cloward, who first utilized the approach for interbody fusion.¹⁰⁻¹² In 1956, Hodgson and Stock concluded: "the anterior approach to the spinal column is a practicable proposition at all levels and is the only approach that allows accurate visual assessment of the extent of the disease."⁶

Crowe and Williams first utilized a transoral approach to remove an osteoma in 1944 and a similar approach was used in 1962 by Fang and Ong to treat six patients with traumatic C1-2 instability^{13,14} (Figs. 36.1 and 36.2). Henry in 1957 described a presternocleidomastoid approach to obtain surgical access to the vertebral artery and transverse apophyses, intertransverse foramina, and nerve roots up to the cervico-occipital region.¹⁵ This approach to the upper cervical spine was also later described and refined by Whitesides and Kelly in 1966.¹⁶ Anterolateral approaches (the high presternocleidomastoid approach,

retropharyngeal, and precarotid) were first described by Smith and Robinson in 1958.¹² Cloward described a similar approach later that year.¹¹ Similar later reports were made by de Andrade and Macnab in 1969 and Riley in 1973.^{17,18}

ANATOMY AND LANDMARKS

A thorough understanding of applied surgical anatomy and superficial landmarks that guide placement of incisions is vital for surgeons utilizing anterior surgical approaches to the cervical spine. The specific surgical anatomy of individual approaches is discussed later in the chapter. Palpable surface landmarks guide the placement of incisions,

as they generally overlie specific vertebrae or disc spaces. These include the hyoid bone (C3 level), thyroid cartilage (C4-5 level), carotid tubercle (C6 level), and cricoid cartilage (C7 level) (Fig. 36.3). Some caution should be used as deep palpation of the carotid tubercle could elicit an intra-operative vasovagal response.

ANTEROLATERAL APPROACH (SMITH-ROBINSON)

Preoperative Considerations

The anterolateral approach to the cervical spine is a utilitarian approach that allows access from C2 to T1 in most patients. Many procedures can be accomplished through this approach, including anterior decompression of the spinal canal (discectomy, corpectomy, epidural abscess evacuation, ventral tumors), anterior cervical fusion (for fracture, deformity, tumors, infection or degenerative processes), biopsy of the vertebral body or disc space and placement of anterior cervical instrumentation.

Certain anatomic considerations may limit the extent of the exposure achieved through this approach. The ability to access the C2-3 disc space depends on the position of the mandible. This can easily be assessed preoperatively on a lateral radiograph. Access to the C7-T1 disc space can be limited by the anatomic position of the manubrium. This again can be assessed on a preoperative lateral radiograph or midsagittal CT imaging. Often, special request to the CT imaging center is required to have the manubrium visualized simultaneously with the sagittal cervical spine images.

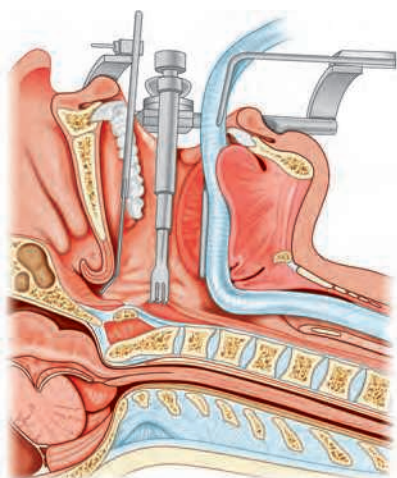


Fig. 36.1: Lateral view of the transoral approach. Diagram view. Include neck in hyperextension and mouth wide open. Include retractor with blade to depress tongue in image.

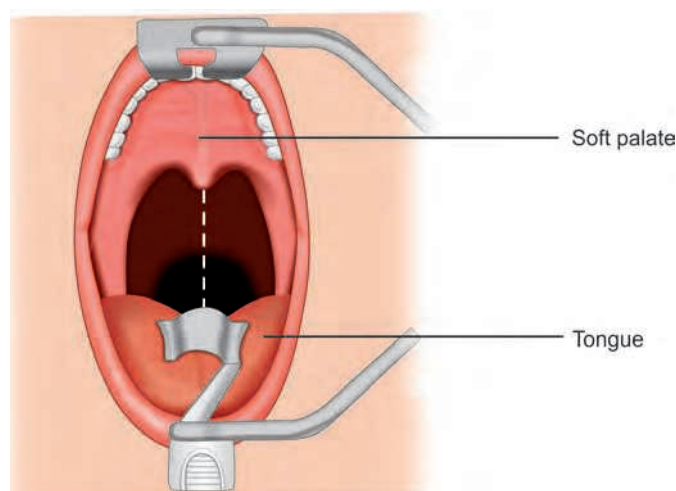
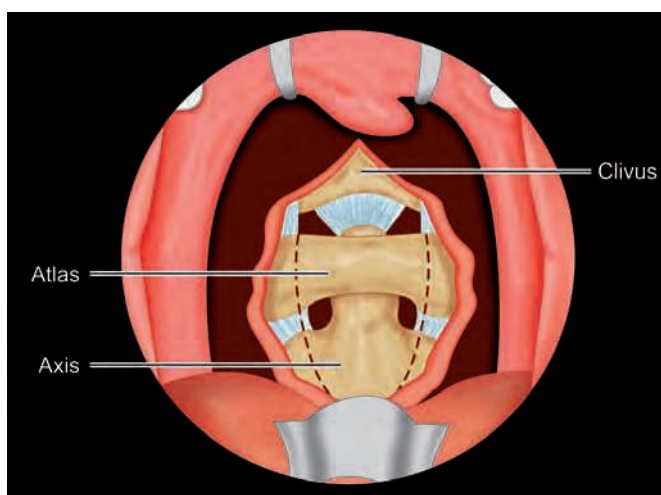


Fig. 36.2: Deep surgical dissection for transoral surgical approach.



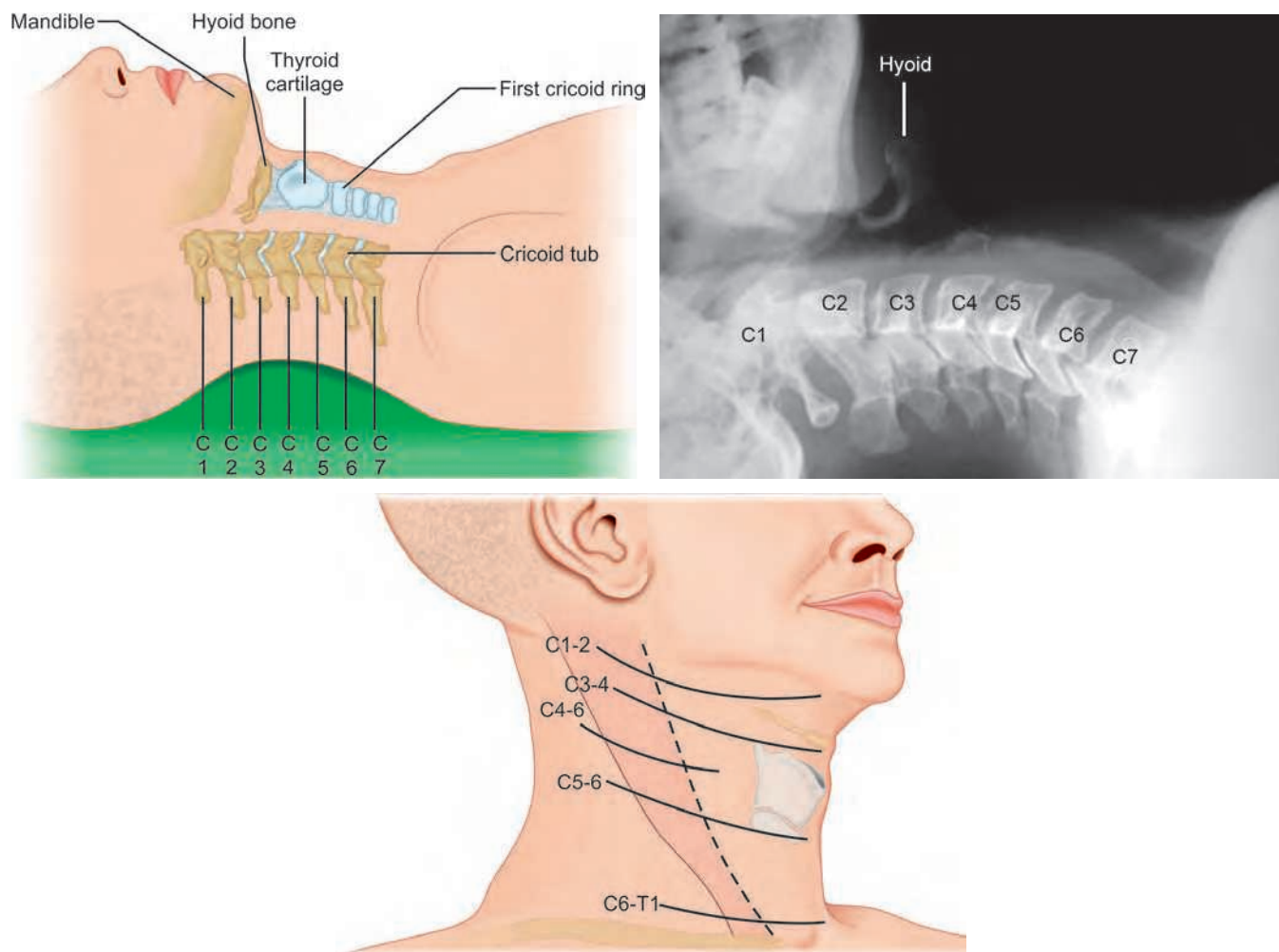


Fig. 36.3: Diagram including side-by-side images showing hyoid bone (C3 level), thyroid cartilage (C4-5 level), carotid tubercle (C6 level), and cricoid cartilage (C7 level).

The patient is placed supine on a regular operating room table with the head in a neutral position or with the neck slightly extended and rotated away from the planned surgical incision. A roll or inflatable bolster beneath the scapulae can be used to facilitate neck extension. The head of the bed can be elevated to 30° to reduce intraoperative venous bleeding. However, it should be noted that placing the patient in reverse Trendelenburg can make it more difficult to visualize the disc in the subaxial spine secondary to its lordotic position. If neurological symptoms are noted with awake extension, an awake or neck-neutral fiberoptic intubation should be considered. The arms are placed at the patients' side, and the shoulders are typically depressed using tape attached to the foot of the bed to improve lateral radiographic visualization of the inferior cervical levels. Caution should be used as

taping the shoulders too aggressively can lead to changes in neurological monitoring secondary to traction on the brachial plexus. Intraoperative traction with Gardner-Wells tongs or Mayfield clamps is rarely necessary except in cases where deformity correction is required¹ (Fig. 36.4).

Incision and Superficial Dissection

Either a transverse or longitudinal/oblique skin incision is made centered over the level(s) of interest as determined by both landmarks and intraoperative fluoroscopy. Transverse incisions are made along Langer's lines, making them more cosmetic, but not as extensible. Extension of the incision past the midline can be useful as it eases soft tissue release. An oblique incision made along the medial border of the sternocleidomastoid has the benefit of being



Fig. 36.4: Image depicting positioning for Smith-Robinson approach. Should include head rotated to right, head of bed up 30°, small rolled up towels behind neck to facilitate extension, shoulders taped to bottom of bed.

more extensible, although less cosmetically appealing (Fig. 36.5). A “J”-shaped incision that combines a transverse incision with an oblique incision can also be used. Superficial surgical dissection begins by identifying the platysma. The fibers of the platysma are divided and the muscle is elevated superiorly and inferiorly. Releasing the subcutaneous fascia off of the platysma is useful to allow the skin opening to be more mobile, thereby making a small incision more extensible. The anterior border of the sternocleidomastoid muscle is identified next, and the deep cervical fascia immediately anterior to the muscle is divided (Fig. 36.6).

Deep Dissection

After palpation of the carotid artery, the pretracheal fascia immediately anterior to the carotid sheath is divided. Division of the pretracheal fascia should be performed just past midline taking caution to avoid the midjugular veins. The pretracheal fascia should be released off of the underlying structures and adequately mobilized. Blunt dissection is used to retract both the sternocleidomastoid and carotid sheath laterally and the sternohyoid, sternothyroid, trachea, and esophagus medially (Fig. 36.7). It is at this point that the obliquely crossing omohyoid is encountered. The omohyoid most commonly crosses the surgical field at the C5/C6 level. It can be identified, mobilized and retracted, or divided intrasubstance after confirmed isolation without sequelae. Typically,

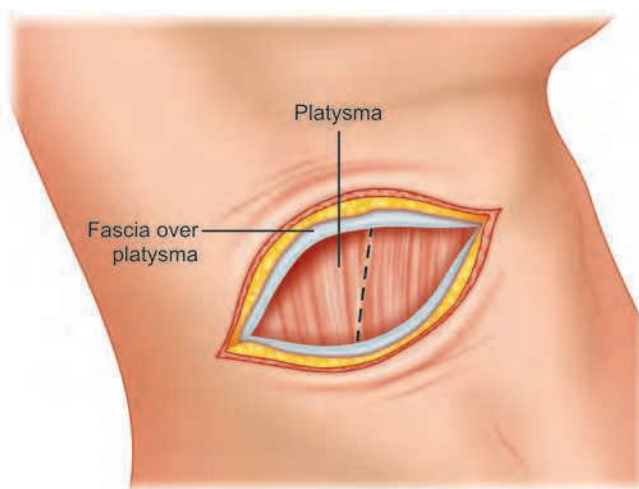


Fig. 36.5: Transverse and/or longitudinal skin incision.

visualization of a multilevel anterior procedure is aided by omohyoid division. Blunt dissection is then used to develop a plane directly down to the anterior surface of the cervical vertebrae, being careful to coagulate or ligate all bleeding vessels to ensure a clear operative field. Care is taken to ensure an adequate longitudinal and lateral release to allow clear visualization and adequate mobilization and protection of the trachea and esophagus together with the recurrent laryngeal nerve (RLN).¹ The prevertebral fascia is bluntly swept off of the anterior longitudinal ligament (ALL) and paired longus colli muscle using a Kittner dissector and peanut. Verification of operative level is traditionally achieved with a double bent spinal needle in the disc space or a tonsil snap clipped to the ALL.

ANATOMIC CONSIDERATIONS AS RELATED TO COMPLICATIONS

Recurrent Laryngeal Nerve

The right RLN branches from the vagus nerve at the level of T1-T2 or inferior. After looping around the subclavian artery, the right RLN becomes invested in the tracheoesophageal fascia inferior to C7-T1. The right RLN travels superiorly, slightly anterior to the tracheoesophageal groove, before coursing between the trachea and the thyroid. After looping around the aortic arch, the left RLN is invested in the tracheoesophageal fascia inferior to the T2 level. The nerve travels slightly anterior to the tracheoesophageal groove and within the tracheoesophageal fascia before coursing between the trachea and thyroid, entering the larynx at

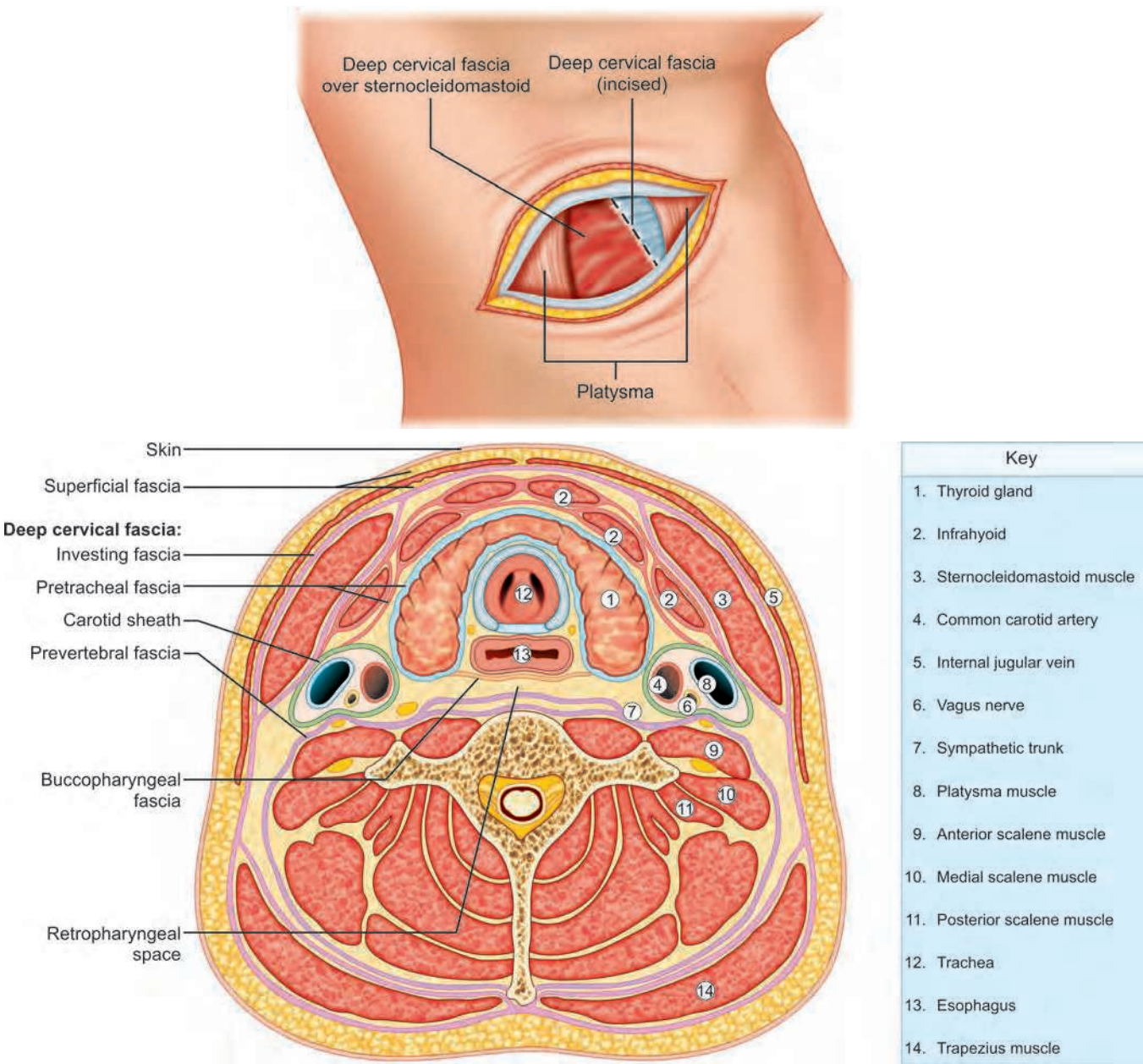


Fig. 36.6: Superficial dissection is identifying platysma, exposing sternocleidomastoid, and deep cervical fascia.

or inferior to C6-7. From an anatomic perspective, there is no appreciable side-to-side difference that could place either nerve under greater risk for injury based on side of approach, nor is there clinically a demonstrated increased rate of palsy based on side of approach.¹⁹ Injury to the RLN is typically a result of traction and pressure, which emphasizes the importance of mobilization. Electrophysiologic monitoring of the RLN has recently been used

to try to reduce injury to the nerve. In patients who have had prior anterior cervical surgery and require revision surgery, preoperative direct laryngoscopy for vocal cord evaluation should be performed if the revision procedure is going to be approached through virgin tissue. Palsy of the nerve requires an approach through the prior incision as damaging the contralateral nerve could potentially lead to palsy of both vocal cords.

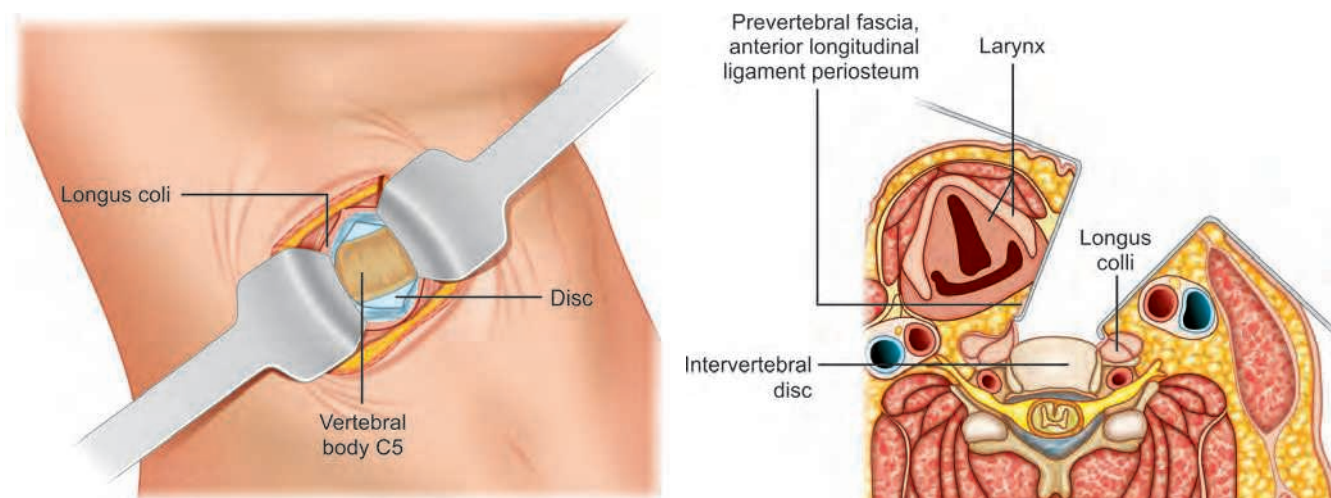


Fig. 36.7: Deep dissection to the anterior cervical vertebrae.

Superior Laryngeal Nerve

The superior laryngeal nerve is found at the C3-4 level and transversely crosses the surgical field travelling with the superior thyroid artery. Injury to this nerve is infrequent, but results in high note phonation and decreased pharyngeal sensation, which can result in pharyngeal phase dysphagia and decreased pharyngeal.

Sympathetic Chain

The sympathetic chain is found on top of longus colli at lower cervical level from C6 and inferiorly. The surgeon should avoid dissecting on top of the longus colli as injury to the sympathetic chain can result in an ipsilateral Horner's syndrome. In addition, cervical retractors should be placed underneath the longus colli muscles and not allowed to migrate anteriorly over the surface of the muscles.

LATERAL RETROPHARYNGEAL (WHITESIDES)

Preoperative Considerations

Whitesides originally described the lateral retropharyngeal approach to the upper cervical spine in 1966 and refined it in 1978.²⁰ The approach was inspired by the work of Henry for exposing the vertebral artery throughout its cervical extent.¹⁵ This approach can be used for anterior access to the upper cervical spine but not the occiput. It is often used for high cervical bony lesions including tumors or infections for which a posterior approach is

not possible. It allows unilateral access to C1 through C3; access to the contralateral side requires a second approach. Unfortunately, this approach may not provide adequate access for anterior decompression or anterior strut grafting.²¹ The advantage of this approach is that it precludes contamination of bone graft from the nasopharyngeal bacterial flora that is inherent with a transoral approach to the high cervical spine.^{22,23}

The patient is placed supine on a regular^{22,23} operating room table with the head in a neutral position or with the neck slightly extended and rotated away from the planned surgical incision. The patient may be placed in halo traction and the approach still accomplished, albeit with difficulty, if instability is present. Nasotracheal intubation opposite the side of surgical incision is preferable. The pinna of the ear on the side of exposure can be sewn anteriorly to improve exposure.

Incision and Superficial Dissection

A longitudinal incision is made along the anterior margin of the sternocleidomastoid muscle. At its superior end, the incision can be carried posteriorly across the base of the temporal bone, and the sternocleidomastoid muscle can be divided at its mastoid origin.¹⁶ The incision can be extended as far as the sternal notch depending on the amount of required distal cervical spine exposure. The subcutaneous tissues and platysma are divided using electrocautery. Blunt dissection is carried out in the subplatysmal plane allowing creation of musculocutaneous flaps. The greater auricular nerve is next dissected out to allow

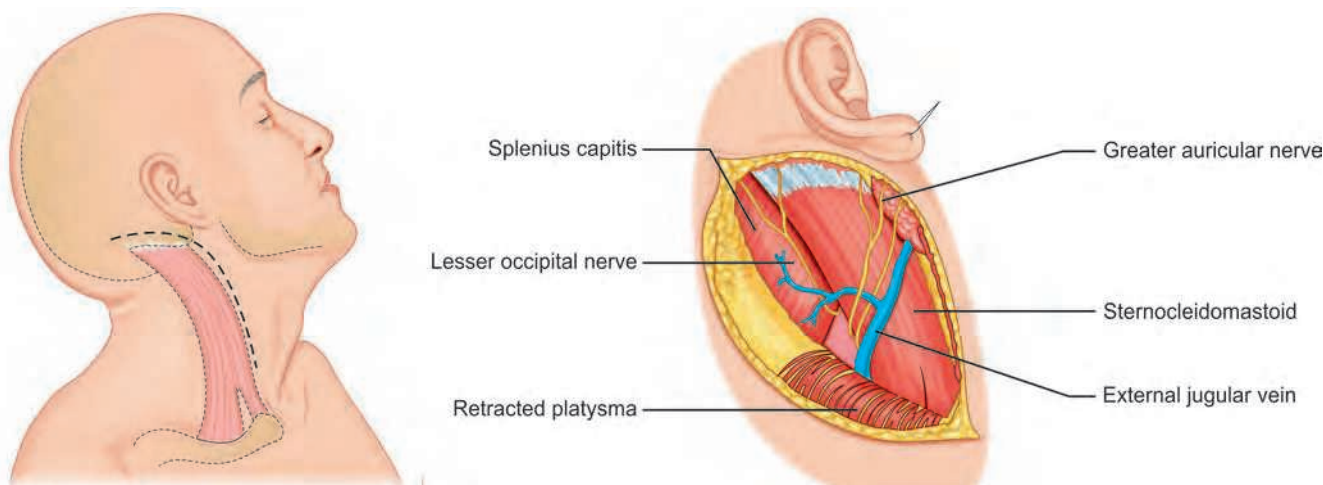


Fig. 36.8: Superficial surgical dissection for lateral retropharyngeal approach.

adequate retraction in a cephalad direction. If it is in the way, it may be resected with a negligible sensory deficit.

The sternocleidomastoid muscle is then everted and the spinal accessory nerve identified as it is approached and passed into the muscle. The accompanying vascular structures are divided and ligated. The sternocleidomastoid muscle is now mobilized and is retracted medially and anteriorly with the carotid sheath. With anterior approaches, the surgeon must dissect the branches of the external carotid artery and laryngeal nerves, retracting the carotid sheath posteriorly. The lateral approach avoids these structures, dissecting posterior to the carotid sheath and retracting it anteriorly (Fig. 36.8).

Deep Dissection

The lateral process of C1 and transverse processes of C2 and C3 are now palpable in the approach. Further dissection along the anterior aspect of the transverse processes and division of Sharpy's fibers allows exposure of the cervical vertebrae. The retropharyngeal space can be opened further with blunt dissection techniques. A sharp elevator or bipolar electrocautery can be used to elevate the longus capitis and longus colli muscles from the transverse processes and lateral masses. Localization is easy because of the prominent, transversely oriented anterior arch of C1 and the prominent vertical midline ridge of the base of the odontoid and body of C2. At the conclusion of the procedure, the sternocleidomastoid is sewn back into place over suction drains. The platysma and skin are closed in layers.

COMPLICATIONS

Adverse events occur infrequently, but several have been described, including esophageal injury, vertebral artery injury, dural tear, postoperative airway compromise, spinal cord injury, hematoma, dysphagia, dysphonia, and graft dislodgement.²⁴ These can be divided into three main categories based on when they typically occur: intraoperative, early (within one week), and intermediate (1–6 weeks).

Intraoperative complications include esophageal injury (0.2–0.4%),^{25–27} vertebral artery injury (0.3%),²⁸ dural tear (3.7%),²⁹ spinal cord injury (0.2–0.9%),^{26,29,30} or peripheral nerve injury (0.2–3.2%).^{24,26,27,31}

Early postoperative complications (within 1 week) include airway compromise due to edema or hematoma,^{29,32,33} epidural hematoma,^{26,27,29} or radiculopathy.^{26,27,31} Intermediate to long-term complications (1–6 weeks postoperatively) include dysphagia,^{34–39} dysphonia,^{34,40–42} or infection.^{26,27} Appropriate strategies must be utilized to avoid these adverse events, and the treating surgeon should have an understanding of how to detect and manage such events when they do arise.²⁴

SUMMARY

Anterior approaches to the cervical spine were developed for dealing with pathologies that arise primarily from the anterior spinal column. The approach chosen depends on a number of factors, including the target spinal segments requiring exposure, the nature of the procedure to be performed, anatomical considerations including deformity, and the patient's body habitus. Additionally,

anterior cervical approaches can complement posterior approaches to allow surgeons to achieve surgical objectives without compromise.

KEY POINTS⁵

- The anterolateral approach is the technique used to surgically address all anterior pathology in the subaxial cervical spine.
- The most common complication of an anterolateral approach in transient dysphagia.
- There is no difference in incidence of RLN injury between right and left sided approach.
- The Whitesides approach yields limited visualization for anterior decompression and strut grafting but eliminates nasopharyngeal contamination of surgical field.

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Anterior Approaches to the Cervicothoracic Junction

Adewale Adeniran, Adam M Pearson

Snapshot

- » Preoperative Planning
- » Superficial Approaches
- » Deep Dissection

INTRODUCTION

The cervicothoracic (CT) junction generally refers to the region from C7 to T5, and the unique anatomic features of the CT junction make anterior exposures very difficult. The commonly used Smith-Robinson anterior approach to the cervical spine is frequently inadequate due to the kyphosis of the thoracic spine and the presence of the sternum that prevents one from accessing the anterior aspect of the vertebral bodies. With a direct anterior approach, one encounters the great vessels and important visceral organs. Lateral approaches via a thoracotomy that are typically performed for approaches to the lower thoracic spine maintain the disadvantages of navigating the visceral organs, while the presence of the scapula and other elements of the shoulder girdle including the brachial plexus limit its usefulness for the CT junction. Fortunately, one rarely needs to access this region anteriorly. Trauma, degenerative conditions, and most deformities can be safely managed with posterior only surgery at the CT junction. The original anterior approach was described by Cauchoix and Binet in 1957 in a classic talk given to the French Academy of Surgery on anterior approaches to the spine.¹ The authors note that the CT elements “have an unhappy reputation for depth and surgical inaccessibility.” They advocated extending a cervical approach inferiorly by using a median sternotomy, and described this approach in a patient with an invasive tumor and spinal cord injury. The exposure was limited caudally to T3, over which the arch of the aorta

was encountered. This extensile approach is extremely morbid and may not be necessary for most procedures at the anterior CT junction, although some authors persist in using it in the setting of deformity correction.² A multitude of less invasive approaches to this important area have been described, yet there remains room for innovation.

PREOPERATIVE PLANNING

The almost straightforward approach to the upper CT junction is the familiar Smith-Robinson anterior cervical approach between the carotid sheath laterally and the esophagus and trachea medially, with its inferior extent limited by the sternum and clavicle. Some upper thoracic or CT procedures can be performed safely without any additional exposure than that afforded by the anterior cervical approach. Unfortunately, there is tremendous variation in patient body habitus and degree of thoracic kyphosis, so the surface anatomy does not consistently correlate with a thoracic level in this region. Obtaining and interpreting orthogonal radiographs prior to surgery is crucial to a successful outcome, and radiographic methods of determining the need for an extended approach have been developed.³⁻⁶ Fraser et al., correlating magnetic resonance imaging landmarks with expert opinion on the feasibility of surgical approach, described a measure called the “instrument manubrial thoracic distance” which correlated best with surgeon opinion on the feasibility of a supraclavicular approach. Their method has been deemed

cumbersome by multiple authors.^{3,4} Karikari et al. have reported their results with a very simple method of determining the lowest accessible level. They define the lowest accessible disc space as that in which a straight line passing through and parallel to the disc space also passes above the manubrium. They consider that screws can be safely placed in the vertebral body immediately below this disc space. In their report of 12 surgical patients, the operative plan never needed to be changed including in two patients with body mass index > 35 and 4 cases where T3 was the lowest instrumented vertebra. Their subsequent review of 50 normal radiographs suggested that the C7-T1 level is accessible from the standard cervical approach in >90% of patients. Cho et al. measured a similar line on lateral plain films in 99 patients and successfully completed the supraclavicular approach in all 99 without need to change their operative plan.⁴ T1 was the lowest instrumented level in 85% of patients in this series, but one patient did have instrumentation to T3. There are no reports about attempting surgery to levels inferior to this line without an extensile approach, so it seems unlikely that this can be done in most patients. Additionally, the CT junction can be difficult to visualize on plain radiographs, so sometimes computed tomography can be a more useful study to determine the feasibility of an anterior approach to this region. Since the typical sagittal computed tomography scan of the cervical spine does not include the manubrium, a special computed tomography scan specifically asking for the manubrium to be included on the sagittal views may be necessary.

As the majority of procedures require access to the midline of the spine, the CT junction can be approached from either the right or left side. There is no evidence of superiority of either side, although a left-sided approach confers a theoretically increased risk of damage to the thoracic duct, while a right-sided approach theoretically places the recurrent laryngeal nerve at risk.

SUPERFICIAL APPROACHES

Median Sternotomy

The classic extensile approach is typically done with direct assistance or immediate availability of a cardiothoracic surgeon. It begins with the Smith-Robinson approach to the cervical spine, along the medial border of the sternocleidomastoid muscle, which is retracted laterally along with the carotid sheath. This incision is then joined with a midline incision over the sternum by dividing the

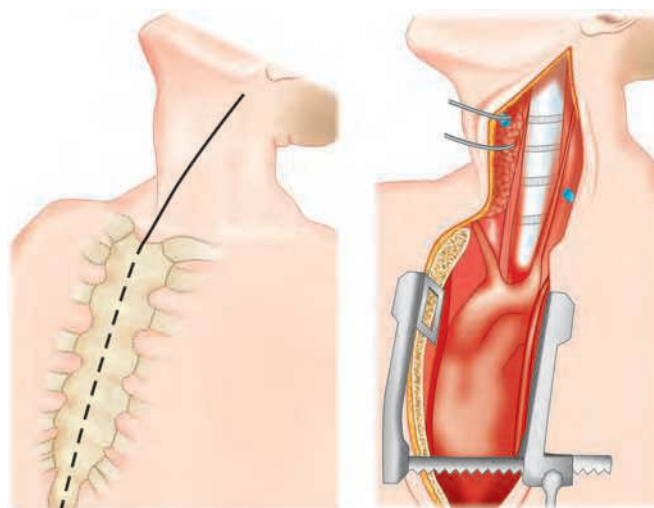


Fig. 37.1: The vertebrae from C4-T4 can be seen between the innominate artery and the aorta.

subhyoid musculature. The sternal incision is carried subperiosteally, and blunt dissection is used to mobilize the retrosternal soft tissues. The sternum is split longitudinally with a saw or osteotomes and retracted widely (Fig. 37.1).^{1,2} Closure is achieved with heavy gauge wires to reapproximate the sternum. Darling et al. modified this exposure by leaving the inferior portion of the sternum intact, dividing the sternum in the midline only to the level of the second intercostal space, before carrying their osteotomy laterally through the synostosis between the manubrium and the body of the sternum.⁷ They report excellent exposure down to the T3 level with this more limited exposure. Nazzaro et al. report an extension of this exposure, in which the incision is curved laterally along the fourth interspace to the midaxillary line.⁸ The internal mammary artery and vein are ligated and the interspace is opened by splitting the fibers of the intercostals. The lung on the operative side is deflated and the arch of the aorta as well as all the great vessels are mobilized inferiorly and controlled with vessel loops. This exposure allows access to lesions that are laterally as well as anteriorly based.

Clavicle Osteotomy

The clavicle osteotomy was developed in order to reduce the morbidity associated with sternotomy yet still allow easy access to the great vessels and provide a viable strut graft. As with a sternotomy, the anterior cervical exposure is carried out initially. The manubrial and sternal heads of the sternocleidomastoid muscle are then elevated from

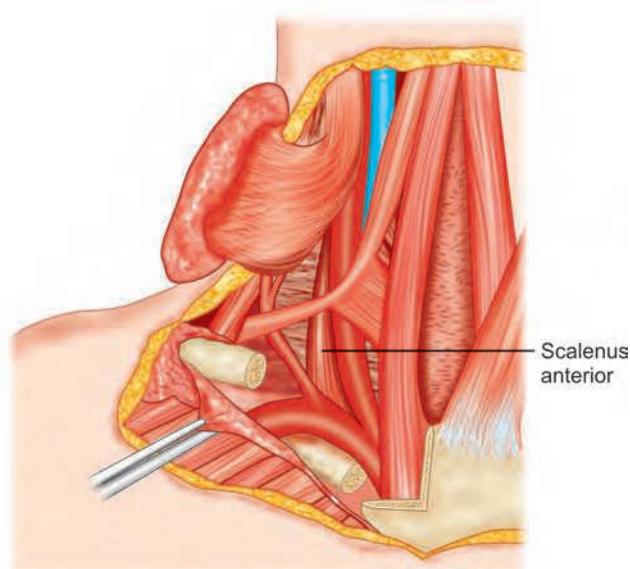


Fig. 37.2: The clavicle and lateral manubrium has been elevated on a muscle pedicle.

their distal attachments and retracted. The medial third of the clavicle is then stripped of its periosteum as is the manubrium on the operative side. The medial clavicle is disarticulated from the manubrium and resected at the junction of the medial and middle thirds and saved to be used as bone graft. The manubrium can either be excised on the operative side or left intact as needed. If additional exposure or graft is needed, the incision can be turned into a T at the level of the sternal notch to allow osteotomy of both clavicles. Other authors maintain the sternoclavicular joint, elevating the lateral manubrium and the medial clavicle on a pedicle of sternocleidomastoid muscle and repairing the construct at the end of the case (Fig. 37.2).⁹ Exposure to the level of T3 has been described using these approaches.¹⁰

Sternal Osteotomy

Attempting to preserve the clavicles, sternoclavicular joints, and sternal body, Pointillart et al. developed a less invasive approach to the midline of the CT junction.⁶ Similar to the other extensile approaches, the standard anterior cervical approach is first undertaken. The sternal origins of the sternocleidomastoid and the infrahyoid muscles are released from their sternal border. A midline incision centered over the manubrium was then carried out to the periosteum, staying medial to the sternoclavicular joints and cranial to the sternal body. Finger dissection was used

to mobilize the retrosternal space, and a high speed burr was then used to thin the posterior cortex of the manubrium. A partial manubrial resection was then completed with Kerrison rongeurs. A long thin retractor then allowed access to the vertebral bodies without need for dissection of the great vessels. This approach typically allows access only down to T2.

DEEP DISSECTION

After initial choice of approach as described above, the surgeon must contend with limitations posed by the internal contents of the chest cavity. Most of the approaches detailed above allow easy access down to the T3 level after blunt dissection through the retrosternal fascia to the level of the vessels, but further caudal extension can be limited. Three predominant corridors have been developed to allow access down to T5.¹¹

Superior Corridor

The superior corridor is the traditional corridor and exists between the esophagus and trachea medially and the left common carotid or brachiocephalic artery laterally. The inferior extent of this corridor is the left brachiocephalic vein, which crosses the field about T3 or T4. Cauchiox et al. suggested ligating this vessel to obtain exposure, but this is rarely necessary as it can be safely retracted in most cases.¹ Excessive superior and inferior retraction in this corridor puts the superior laryngeal and recurrent laryngeal nerves at risk respectively. The sympathetic trunk lies between the posterior sheath of the carotid and the fascia of the longus colli and must be protected with a handheld blunt retractor (Fig. 37.3).

Middle Corridor

The middle corridor lies between the right brachiocephalic vein and artery and is exposed by retracting the right brachiocephalic vein to the patient's right. This must be done carefully as venous rupture has been described and can be catastrophic. The inferior limitation of this corridor is the confluence of the left and right brachiocephalic veins, which usually occurs at the T4 level¹¹ (Fig. 37.3).

Inferior Corridor

The inferior corridor allows exposure to T5 and is bordered by the superior vena cava on the right, the ascending aorta on the left, the left brachiocephalic vein superiorly, and

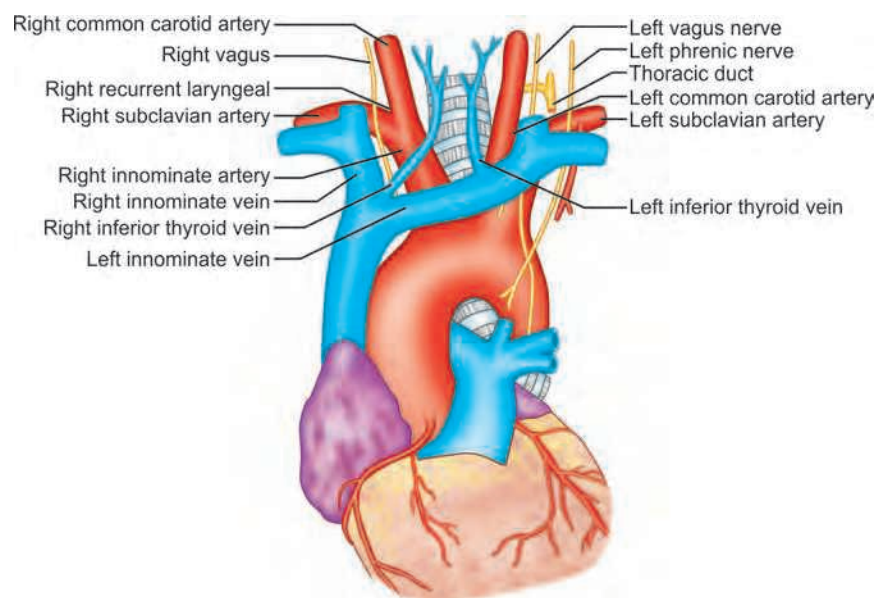


Fig. 37.3: The innominate (brachiocephalic) artery, veins, and tributaries.

the right pulmonary artery inferiorly. The tracheal bifurcation most commonly lies about the body of T4 and may act as an inferior restraint as well (Fig. 37.3).¹¹

CONCLUSION

Anterior approaches to the CT junction are technically challenging and are associated with high levels of morbidity. When possible, a posterior approach is favored. In cases in which oncologic principles of wide resection are being followed or if anterior column support is required and cannot be accomplished from a posterior approach, these approaches can provide access to this challenging region of the spine. Obtaining the assistance of a cardiothoracic surgeon is recommended for those unfamiliar with these approaches.

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Evaluation and Treatment of Axial Neck Pain

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Snapshot

- » Etiology/Classifications
- » Evaluation

- » Treatment
- » Case Examples

INTRODUCTION

Neck pain is a very common complaint that is frequently encountered in primary care and spine clinics. Most people can expect to have episodes of neck pain during their lifetime, but a majority will not have neck pain that interferes with normal activities. Diagnosing and treating the cause of axial neck pain can be difficult, and even when there is a clear diagnosis for the symptomology, often times, there is no intervention that can predictably cure the cause of pain. The goal of this chapter is to define the etiology of axial neck pain and review the appropriate evaluation (history, physical, and radiographic) and treatment (operative and nonoperative) for this problematic disorder.

ETIOLOGY/CLASSIFICATIONS

Neck pain has been reported in the literature to occur in 66% of all individuals at some point during their lifetime.^{1,2} The most common cause of axial neck pain is age-related arthritis of the cervical spine. The degeneration of the cervical spine associated with osteoarthritis has been coined cervical spondylosis and is found in most aging individuals.^{2,3} Cervical spondylosis can have many presentations including axial neck pain, radiculopathy, myelopathy, or any combination of these symptoms. Unlike axial neck pain, the pathogenesis of radiculopathy and myelopathy are well understood and are related to compression of the cervical nerve roots or the spinal cord, respectively.

There are modifiable and nonmodifiable risk factors that have been shown to be associated with axial neck pain. Nonmodifiable risk factors include age, gender, and genetics. Modifiable risk factors associated with axial neck pain include tobacco use, low physical activity, sedentary work position, repetitive work, and precision work.⁴

Although the mainstay of treating axial neck pain is nonoperative, there have been several articles that advocate surgical intervention with beneficial results when the correct indications exist.^{2,5-9} Nonoperative modalities are commonly used with good results, but neck pain can be recurrent with 50–85% of people reporting recurring neck pain within 5 years of the initial event.⁴

The Task Force on Neck Pain and Its Associated Disorders in 2009 proposed a classification system to describe four different grades of axial neck pain in order to define a consensus on the severity of the axial neck pain when designing research and future health care policy.⁴ The classification is based on patients' subjective evaluation of pain and the clinician physical examination and radiographic evaluation. The classification is outlined in Table 38.1.

EVALUATION

The successful treatment of axial neck pain greatly depends on identifying the source of pain. There are many causes of axial neck pain including muscular strains, ligamentous

Table 38.1: Classification of axial neck pain.

<i>Grades</i>	<i>Signs, symptoms, and treatments</i>
Grade I neck pain	No signs or symptoms of structural pathology. Minor interference with daily activity. Responds to minimal intervention
Grade II neck pain	No signs or symptoms of structural pathology. Major interference with daily activity. Requires pain relief and early activation/intervention
Grade III neck pain	No signs or symptoms of structural pathology, but some neurological signs such as decreased reflexes, sensory changes, and/or weakness that warrants further radiographic workup
Grade IV neck pain	Signs or symptoms of major structural pathology, such as fracture, myelopathy, neoplasm, or systemic disease; requires prompt investigation and treatment

sprains, degeneration of the cervical disks, facet joint degeneration/arthritis, upper cervical and occipital/cervical arthritis, and rheumatoid patients with synovial erosions and instability.

Muscle strains and ligamentous sprains are usually made as a diagnosis of exclusion after structural diagnoses have been ruled out. They are usually associated with poor posture/ergonomics, work and personally related stress, traumatic injury such as a whiplash injury, and/or chronic muscular fatigue. Muscular pain can also develop secondarily, as a protective mechanism, to another primary source of pain coming from the shoulder, scapular dyskinesis, temporomandibular joint, and cervical pathologies including malignancies.^{10,11} The exact physiology of muscular/ligamentous pain generation is not fully understood but is thought to be secondary to the sensitization of the free nerve ending found in the muscular/ligamentous units.

Degeneration of the intervertebral disks is a normal part of aging and is associated with spondylosis, however, while most people eventually have degeneration of their intervertebral disk, not everyone presents with clinically significant axial neck pain. The peripheral portions of the cervical disks contain nerve fibers and endings from the sinuvertebral nerve that may be responsible for pain generation, especially with degeneration.^{12,13}

Facet joints (also known as zygapophyseal joints) are synovial joints that contribute to the posterior column on the cervical spine. Facet joints have been shown to cause

axial neck pain in experimental models. In an in vivo study evaluating the facet joints, normal patients with no axial neck pain had their facet joints injected with normal saline and patients responded with neck, head, and shoulder pain.¹⁴ This pain distribution was reversed when anesthetic injections were placed blocking the dorsal primary rami that is responsible for pain recognition in the facet joints.¹² These studies both demonstrate that the facet joints can be a source of axial-neck pain.

Upper cervical and occipital-cervical junctional arthritis can cause axial neck pain and occipital headaches. In another injection study, the authors demonstrated reproducible pain patterns with injections into the atlanto-occipital and atlantoaxial joints.¹⁵ In particular, patients can develop osteoarthritis of the C1-2 joint that can cause severe pain in the suboccipital joint region exacerbated by axial rotation¹⁶ (see Fig. 38.4).

Another generator of pain is irritation of the greater occipital nerve, a branch of the C2 nerve. The C2 nerve can be compressed or chemically irritated with atlantoaxial arthritis or pannus formation from rheumatoid disease. Rheumatoid disease is also known to cause axial neck pain caused by a multitude of pathologies including atlantoaxial instability, superior migration of dens and basilar invagination, and subaxial instability.

Although uncommon, upper cervical nerve compression at C3 or C4 from the C2/3 or C3/4 level does not typically radiate to the extremities and must be ruled out with magnetic resonance imaging (MRI) and diagnostic nerve root injections. Upper cervical nerve compression should not be confused with axial neck pain that is facet or disc related.

History and Physical Examination

As with many maladies in clinical medicine, the history and physical examination are of utmost importance. Axial neck pain and whiplash-associated disorder (WAD) typically present with posterior midline tenderness that can radiate to the shoulder and occiput. Stiffness and headaches are very common and so are descriptions of warmth and tingling.¹⁷ Patients with osteoarthritis of the C1-2 lateral mass joints can have severe pain with axial rotation of the head. Typically, these patients point to their suboccipital region lateralizing to the side of the arthritis. These patients will demonstrate significant decrease in their range of motion and increasing pain while turning toward the affected side.

One should do a careful neurologic examination to rule out pain in a dermatomal distribution, changes in sensory

patterns in the upper extremities, and blunting of reflexes. Myelopathic signs including a positive Hoffman's examination (flexion of thumb and index finger after rapid middle finger distal interphalangeal joint flexion), clonus (repetitive plantar flexion of ankle after forced dorsiflexion of ankle) or a present Babinski reflex (great toe extension after stroking plantar foot surface). If any of these findings are noted on physical examination further radiographic work-up is necessary to rule out spinal cord compression. Patients with axial neck pain typically do not display such findings. In patients who present with radicular or myelopathic symptoms and axial neck pain, the neurologic symptoms take priority in the treatment regimen.

Radiographic Imaging

Radiographic imaging for general axial neck pain can be very misleading because of its sensitivity in identifying abnormalities that may not be contributing to the current symptoms. Studies of patients between 50- and 65-year-old have shown a 79% incidence of disc space narrowing, end plate sclerosis, or osteophytes.¹⁸ Another study evaluating MRI in asymptomatic subjects demonstrated that in patients under 40 years of age there was a 14% incidence of bulging/herniated disks, foraminal stenosis, disc space narrowing, or abnormal cord signal change.¹⁹ The same study demonstrated an incidence that was double (28%) if the patient was over 40 for the same findings.¹⁹ The oversensitivity of radiographic imaging must be taken into account when examining patients with axial neck pain and imaging should be avoided if there is a normal neurological examination and no concern for trauma or instability. The National Emergency X-ray Use Study (NEXUS) is an excellent clinical study that was designed to determine the indication for imaging in patients with traumatic injuries and concern for cervical spine injury. National Emergency X-ray Use Study was a multicenter, prospective observational study designed to determine what clinical criteria indicate the need for radiographic imaging of the spine in blunt cervical spine trauma patients. The study had over 34,000 patients with blunt trauma to the head and neck. The study evaluated five clinical criteria that included midline cervical tenderness, focal neurological deficits, normal cognition, level of intoxication, and painful and distracting injuries (Table 38.2). The study demonstrated that out of the 34,000 patients, there were 818 cervical spine injuries, and of these 818 injuries, 810 were detected using these criteria, resulting in only 8 injuries being missed. This equates to a negative predictive value of 99.8% and a sensitivity of 99%.

Table 38.2: NEXUS clinical criteria.

Five components to clear cervical spine

- (1) No midline cervical tenderness
- (2) No focal neurologic deficit
- (3) Normal alertness
- (4) No intoxication
- (5) No painful, distracting injury

The criteria led to a reduction in the use of unindicated radiographs by 12.9%. The final conclusion of the NEXUS study was that there was an extremely low probability of c-spine injury if all five criteria were met.^{20,21} While this study was designed to determine if emergency medicine doctors should obtain advanced imaging, it also applies to the clinicians in primary care and surgical spine clinics. In a fully conscious patient with cervical trauma/WAD, the spine can be cleared with very high confidence using the same five clinical criteria. If any of the criteria are not met then radiographs should be obtained.

When history and physical examination is concerning for the diagnosis of C1-2 lateral mass arthritis, an open-mouth odontoid view of the cervical spine should be performed. Joint space narrowing secondary to loss of articular cartilage can be easily seen (see Fig. 38.4). If an open-mouth odontoid view cannot be obtained easily, CT scans can be performed to confirm the diagnosis. Occasionally, in the absence of joint space narrowing, MRI can often show inflammation of the C1-2 joint on the short inversion time inversion recovery (STIR) images.

TREATMENT

Nonoperative Treatment

Nonoperative therapy should always be the first line of treatment once structural instability and neurological compromise are ruled out. There is a paucity of high-quality evidence for the nonoperative treatment of axial neck pain. The Task Force on Neck Pain and Its Associated Disorders performed a meta-analysis of the literature reviewing over 31,000 citations regarding axial neck pain and what they found was that they had a difficult time creating any consensus statements due to the variability of the disorder, treatment modalities and outcomes.⁴ Nonoperative modalities include medical therapy, physical therapy, general health promotion, injection therapy, and radiofrequency ablation. There is a lack of clinical studies to support many of these modalities and much of the research has focused on low-back pain treatment.

Table 38.3: Nonoperative modalities.

<i>Modalities with clinical literature to support use</i>	<i>Modalities with NO clinical literature to support use</i>
Early return to normal activities ^{16,23,27}	Immobilization ^{27,31}
Supervised exercises and physical therapy ^{25,28}	Transcutaneous electrical nerve stimulation ^{16,28}
Chiropractic manipulation and mobilization ^{16,27,29,30}	Cervical traction ^{16,28,30,31}
Pulsed electromagnetic field therapy ^{27,30,31}	

Medical treatment is usually one of the first treatments for axial neck pain. There are multiple medications that can be used. Tylenol can be used in doses from 2 g to 4 g per day. It must be avoided in patient who are elderly, have a history of alcoholism/liver disease, taking other medications metabolized by the liver, and can still be toxic at recommended doses in these populations.²² Nonsteroidal anti-inflammatory drugs (NSAIDs) are also a first-line medication. They must be used with care because they have been shown to cause gastric ulcers and bleeding especially in the elderly. COX-2 inhibitors are recommended over traditional NSAIDs in the geriatric population.²³ These drugs should be used especially when the cause of the axial neck pain is thought to be arthritic or inflammatory in nature. Muscle relaxants have been shown to be efficacious in axial neck pain that is associated with neck spasms. They are, however, habit forming and have several side effects including nausea, somnolence, and decreased respiratory drive. Muscle relaxants are not recommended for the use in acute WAD injuries because of limited evidence of efficacy.^{17,24} Opioids are extremely efficacious in axial neck pain but should only be used for acute onset neck pain and should not be treatment modality for long-term chronic pain.²⁵ There are several side effects including physiologic dependence, constipation, sedation, and nausea. Antidepressant medications are widely used and have been documented in the literature to be efficacious for chronic pain syndromes and are frequently used in recalcitrant axial neck pain.^{23,25-27} There is often associated depression in patients with chronic axial neck pain that may also be helped with the use of antidepressant medications.

Physical modalities are often used for the treatment of axial neck pain and there is a wide range of interventions available. The literature once is diverse with regard to supporting their use and efficacy (Table 38.3).

Modalities with Clinical Evidence

Early return to usual activities has been shown to be clinically helpful especially in WAD.^{17,24,28} Supervised exercise and physical therapy have been shown efficacious for the treatment of acute onset axial neck pain and chronic neck pain.^{26,29} Chiropractic manipulation and mobilization have been shown to provide short-term relief of axial neck pain.^{17,28,30,31} Pulsed Electromagnetic Field Therapy has been shown to cause significant reductions in pain and increase in cervical range of motion in several high-quality studies.^{28,31,32}

Modalities with Little Clinical Evidence

Immobilization has been shown to provide no benefit in three studies for use in axial neck pain.^{28,32} Its use has only been recommended for 3 days or less when treating for WAD and if used beyond this has been shown to prolong disability.^{17,24} Transcutaneous electrical nerve stimulation and therapeutic ultrasound, while reported by most patients to relieve pain during treatment, have had several studies demonstrate no evidence of effect with regard to curative effects.^{17,29} Cervical traction, while widely used by physical therapists and as home units, has multiple high-level studies showing no long-term effect for its use in axial neck pain.^{17,29,31,32}

It is important to counsel patients about overall health with regard to weight, smoking cessation, and aerobic exercise. In epidemiologic studies axial neck pain is associated with overall poor general health status including obesity.³³⁻³⁵ There are, however, no clinical studies showing a direct correlation with weight loss and the reduction of axial neck pain. There have been a multitude of studies looking at the relationship between back pain and smoking. Since there are no clinical studies specifically looking at smoking and axial neck pain, results extrapolated from the axial low back pain literature should be examined with caution. Nonetheless, a large meta-analysis of over 47 epidemiologic studies concluded a direct correlation between smoking cessation and decreased axial back pain.³⁶ For this reason, we always counsel our axial neck pain patients on weight loss and smoking cessation. Aerobic exercise is also an important treatment modality in patients with axial neck pain, and there have been multiple studies demonstrating its effectiveness.³⁷⁻³⁹

Injection Therapy

There are a host of injection techniques that can be utilized for axial neck pain including trigger point, facet, nerve

root, and epidural injections. The literature is equally split in favor and against the use of these types of injection for axial neck pain with most publications only recommending their use in patients with true radiculopathy.^{40,41}

Operative Treatment

Accepted criteria for surgical intervention for axial neck pain exists mainly when the axial neck pain associated with a concurrent diagnosis of radiculopathy, myelopathy, or instability in the cervical spine. Indications for surgical intervention for axial neck pain alone are less clear and are more to the discretion of the practitioner and the patient's wants and needs. Most practitioners will only reserve surgical interventions for axial neck pain in patients who have exhausted all other conservative measures over a 6–12-month time period. Historically, results for surgical intervention of axial neck pain have demonstrated satisfactory results from 63% to 73% in patients.^{42–46} There are several recent articles in the literature that support surgical intervention for recalcitrant axial neck pain with good to excellent results being demonstrated. Palit et al. prospectively collected data on 38 consecutive patients who underwent anterior cervical discectomy and fusion for axial neck pain without signs/symptoms of radiculopathy or myelopathy.⁷ Their results showed that there was a significant reduction in visual analog scale neck pain scores and Oswestry disability questionnaire scores. Almost 80% of the patients were satisfied with their outcomes at 53 months of follow-up. Their data also demonstrated that there was not a difference between workers compensation claims and private insurance patients with regard to improvement. In another clinical study Ratliff et al. retrospectively studied 27 consecutive patients who underwent surgical intervention for axial neck pain without radiculopathy/myelopathy.⁸ In their series they had over 85% patient satisfaction, with over 95% stating they would repeat the surgical procedure for their neck pain. While these studies are subjected to selection and recall bias, they provide insight into outcomes associated with surgical management of axial neck pain. Overall, the literature suggests that operative treatment of degenerative disc disease in the cervical spine is more successful than in the lumbar spine. In addition, patients with recalcitrant pain due to C1-2 osteoarthritis may benefit from a C1-2 posterior arthrodesis and have been reported to have good results.¹⁶

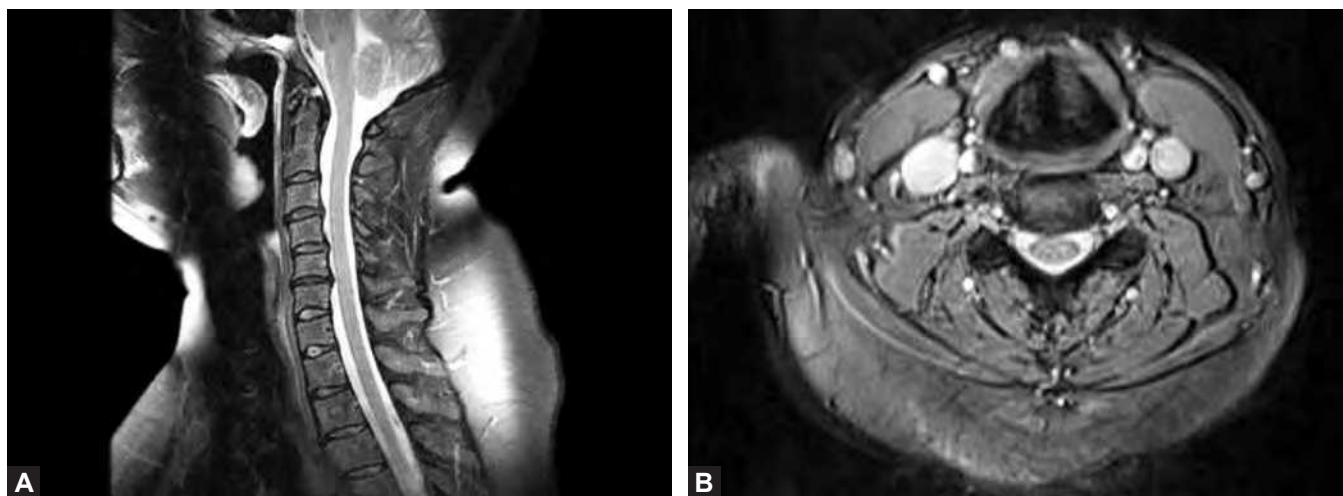
CASE EXAMPLES

Case 1

Case 1 is a 50-year-old healthy female who presented with 1 year of axial neck pain without radicular or myelopathic symptoms. Radiographs showed multilevel degenerative disc disease without instability (Fig. 38.1). An MRI demonstrated multilevel disc degeneration without significant foraminal or central stenosis. She was treated for 2 years with conservative measures including physical therapy, chiropractic manipulation, and NSAIDs. She presented back to our office 3 years after initial onset of axial neck pain with recalcitrant axial neck pain and disability. A repeat MRI (Figs. 38.2A and B) demonstrated a small central herniation at C5/6 without foraminal stenosis. Since she failed a complete nonoperative course and did not have external motivators, she was offered surgical treatment. Her post-operative radiographs are seen in Figure 38.3. At 3-month follow-up, all of her axial neck pain had resolved. This case is an exception for our practice as neck pain from multilevel



Fig. 38.1: Preoperative films of patient with axial neck pain and no signs of radiculopathy or myelopathy. Note the kyphosis in the cervical spine along with the multilevel degenerative disc disease.



Figs. 38.2A and B: Preoperative magnetic resonance imaging of patient. Sagittal film (A) shows multilevel degenerative disc disease but no significant stenosis. Axial image (B) demonstrates small central herniation at C5/6 but no foraminal stenosis.



Fig. 38.3: Postoperative films of patient with axial neck pain who failed 3 years of conservative therapy. Note the restoration of cervical lordosis and incorporation of anterior iliac crest bone graft at 3 months post-operation.



Fig. 38.4: Preoperative films of patient with axial neck pain and no signs of radiculopathy or myelopathy. Note the severe osteoarthritis in the right C1/C2 lateral mass complex (arrow).

degenerative disc disease is almost never treated operatively. Careful patient education of expectations following degenerative disc disease surgery is mandatory.

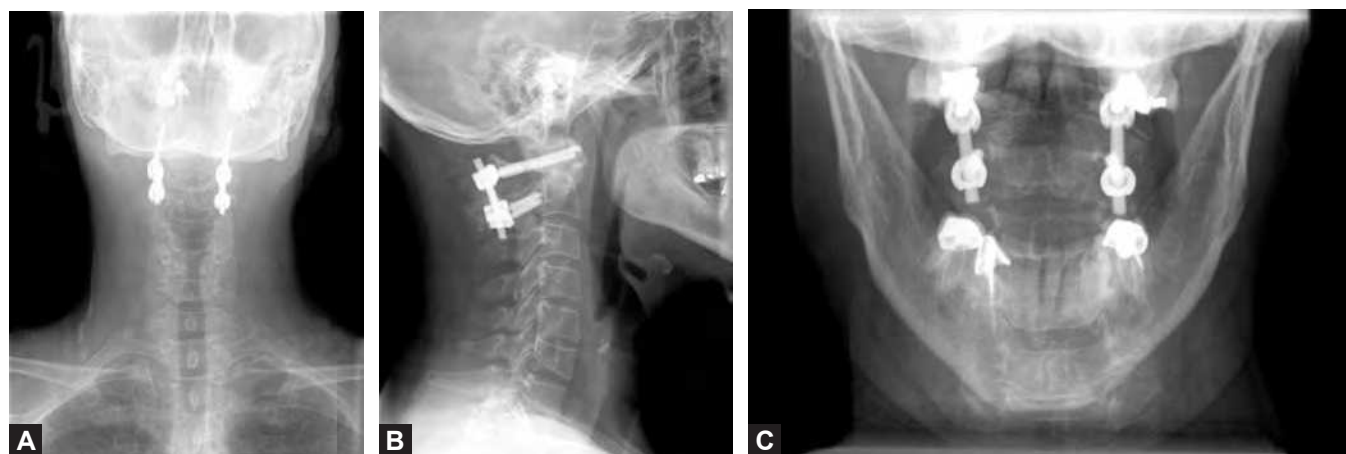
Case 2

Case 2 is a 55-year-old female with 3 years of axial neck pain localized to the right suboccipital region. On physical

examination, she had limited rotation to the right side. She had no signs or symptoms of radiculopathy or myelopathy. Open-mouth odontoid and lateral view of the cervical spine are seen in Figures 38.4 and 38.5. Severe osteoarthritis is noted in the right C1-2 lateral mass articulation. The patient underwent multiple nonoperative modalities including physical therapy with traction, epidural steroid injections, NSAIDs, and immobilization. The patient was ultimately



Fig. 38.5: Preoperative films of patient with axial neck pain and no signs of radiculopathy or myelopathy. Note the severe osteoarthritis in the C1/C2 lateral mass complex (arrow).



Figs. 38.6A to C: Anteroposterior, lateral, and open-mouth odontoid views status post C1/2 posterior spinal fusion using the Harm's technique for severe C1/2 osteoarthritis.

treated with a C1-2 posterior arthrodesis using the Harm's technique⁴⁷ (Figs. 38.6A to C). As anticipated, she ultimately lost 50% of her flexion/extension and axial rotation but had total resolution from her axial neck pain.

CONCLUSION

Axial neck pain is a ubiquitous complaint in primary care and most spine surgeon's offices. There are a plethora of pathologies that can cause axial neck pain usually related to biomechanical changes associated with aging and associated cervical spondylosis. However, acute onset axial neck pain from trauma and recalcitrant neck pain associated with rheumatologic disorders and malignancies must be ruled out. The patient history and physical and radiographic imaging, if warranted, can usually lead the practi-

tioner to make a diagnosis of the pathogenesis of the axial neck pain.

The available treatment modalities are abundant, but the evidence to support most modalities is lacking. Luckily most episodes of axial neck pain, without any significant intervention, will recover over time. When recalcitrant axial neck pain has failed nonoperative modalities surgical intervention may be warranted depending on the source of the axial neck pain. Unfortunately, there are no prospective, randomized studies in the literature evaluating the operative outcome of patients with axial neck pain. However, there are several studies in the literature that demonstrate improved clinical and functional outcome for patients with recalcitrant axial neck pain that have failed multiple conservative measures.

KEY POINTS

- Axial neck pain is ubiquitous in the general population with approximately 70% of the population having an episode of axial neck pain within their lifetime.
- Conservative treatments including physical therapy, structured exercise, weight loss, smoking cessation, and chiropractic manipulation have been shown to improve axial neck pain.
- Surgical treatment should be reserved for recalcitrant axial neck pain patients that have completed most of the noninvasive modalities and who persistently have symptoms of axial neck pain.

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Cervical Spondylotic Radiculopathy: Clinical Evaluation and Nonoperative Treatment

G Balamurali, S Rajasekaran

Snapshot

- » Pathophysiology
- » Natural History of Cervical Radiculopathy

- » Injection Management

INTRODUCTION

Cervical radiculopathy is a dysfunction of a cervical spinal nerve root arising from compression and inflammation of the root near the cervical neural foramen. Clinically patients present with pain in the neck and one arm, with a combination of sensory and motor loss, with or without reflex changes in the affected nerve root distribution.^{1,2} The reported incidence of cervical radiculopathy is between 0.85 and 3.5 per 1,000 population with peak incidence around 50–54 years of age.^{3–5}

The most common cause of radiculopathy is neural foramen encroachment due to cervical spondylosis with hard osteophyte compression and/or a soft cervical disc herniation. Unlike in lumbar disc herniation, a true herniation of the nucleus pulposus is uncommon in cervical disc disease.⁶ Other factors such as hypertrophied facet joint, uncovertebral joint hypertrophy, disc protrusion, and spondylotic spurring of vertebral body also often play a variable role either individually or in combination. Less common causes of cervical radiculopathy are intra- or extra-spinal tumors, traumatic root compressions or avulsions, synovial cyst, meningeal cysts, and dural arteriovenous fistulae.²

PATHOPHYSIOLOGY

The primary pathology of cervical spondylosis starts within the intervertebral disc and later progresses to secondary mechanical changes in the surrounding facet joints and

soft tissue structures. Decreasing water content from 90% at 30 years to <70% by the eighth decade, changes in the ratio of proteoglycan to collagen and keratin sulfate to chondroitin sulphate in nucleus pulposus makes the disc more compressible and less elastic.⁷ This subjects the annular fibers to excessive compression and shear forces, causing weakening and tearing of their outer layers, potentially leading to a soft disc herniation. Reduction in the intervertebral disc height also leads to ligamentum flavum buckling, osteophyte formation, hypertrophy of the uncovertebral and facet joints. This process leads to encroachment of the neural foramen that is referred to as hard disc.² The origin of pain in cervical radiculopathy is multimodal and includes release of inflammatory mediators during the disc prolapse and compression of the dorsal root ganglion (Fig. 39.1).^{8,9}

Clinical Presentation

Acute, subacute, and chronic types of cervical radiculopathic presentations have been reported.² Acute cervical radiculopathy occurs in the setting of soft disc herniation in younger age group individuals. Patients without persistent symptoms with pre-existing cervical spondylosis present with subacute radiculopathy. They develop insidious symptoms, which are often polyradicular in nature. Acute and subacute radiculopathies that fail to respond to treatment progress to chronic radiculopathy.

Pain radiating to the arm is the most common symptom followed by sensory deficit, neck pain, diminished

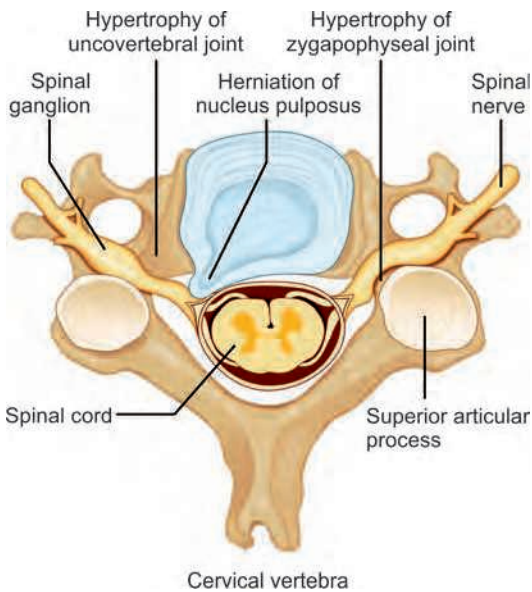


Fig. 39.1: Pathophysiology of cervical nerve root compression.

reflexes, and motor deficit in a series of 800 patients with cervical radiculopathy (Table 39.1). Sensory symptoms like paresthesia and numbness often do not follow a sensory dermatomal pattern. In acute cervical radiculopathy, patients experience pain in the myotomal distribution rather than a distal dermatomal distribution.² Common patterns of presentation are shown in Table 39.2.

Tanaka et al.¹¹ proposed that neck or periscapular pain often precede arm or finger symptoms in cervical root compression based on their experience during diagnostic root injections (Fig. 39.2). As the needle is inserted around the root, patients perceive neck or scapular pain first followed by arm or finger pain. It is also common in clinical practice to see patients with only neck or scapular pain unaccompanied by radicular symptoms in the arm or fingers. Pain in the suprascapular region indicates C5 or C6 radiculopathy, pain in the interscapular region corresponds to C7 or C8 radiculopathy, and pain in the scapular region to C8 radiculopathy (Fig. 39.3).

Clinical Examination

Local pathologies around the shoulder and scapular region should be excluded before attributing the pain to cervical root involvement. To differentiate cervical radiculopathy from other sources of pain, provocative tests specific to cervical nerve roots have been explained. Spurling's sign is elicited by hyperextending the neck and rotation toward the symptomatic side, resulting in reproduction of the arm

Table 39.1: Clinical presentation of cervical radiculopathy.¹⁰

Arm pain	99.4%
Sensory deficit	85.2%
Neck pain	79.7%
Reflex deficits	71.2%
Motor deficits	68%
Scapular pain	52.5%
Anterior chest pain	17.8%
Headaches	9.7%
Anterior chest and arm pain	5.9%
Left-sided chest and arm pain	1.3%

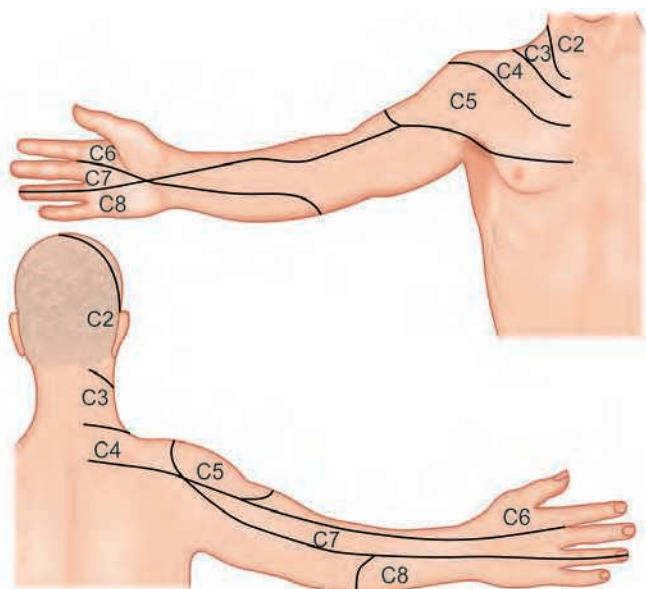
pain. This maneuver diminishes the available area in an already compromised neural foramen, leading to further nerve root compression. This test is specific but not sensitive for cervical radiculopathy. Axial compression test, in which compression over the skull may diminish the height of the foramen and reproduce symptoms, is a less reliable provocative sign. Valsalva maneuver also increases the radicular pain (Fig. 39.4).

Davidson et al. described shoulder abduction sign wherein patient experiences relief of arm pain with shoulder abduction.¹² Shoulder abduction brings about pain relief by shortening the course of the nerve and relieving the compression (Fig. 39.5).

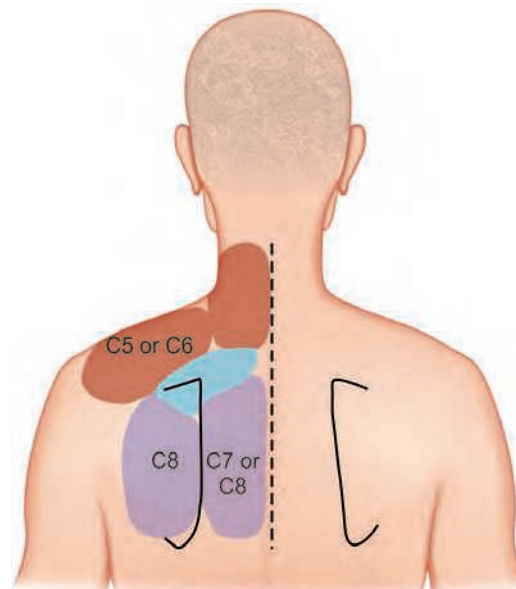
Systematic and proper clinical examination in cervical radiculopathy would lead us to the level of compression and root involved. The most common nerve roots involved in cervical radiculopathy are the C6 and C7 roots due to C5-C6 and C6-C7 disc pathology, respectively. Patients with C7 radiculopathy present with pain along the posterior aspect of the shoulder, over the triceps and dorsal aspect of middle finger. Triceps weakness may not be noticed by the patient until it becomes severe, since elbow extension is aided by gravity. The C6 nerve root is the second most common nerve root involved in cervical radiculopathy and the patient usually presents with pain radiating from the neck to lateral aspect of forearm, thumb and the index finger and dorsal aspect of web space between them. Although many groups of muscles are supplied by the C6 root, wrist extensors are predominantly affected. C5 radiculopathy, which is the next most common root involved, results from pathology at the C4-C5 disc and presents with pain along the lateral aspect of the shoulder associated with numbness. Deltoid and supraspinatus are the primarily affected muscles, weakening the shoulder abduction.

Table 39.2: Cervical radiculopathy and associated sensory, motor, and reflex disorders.

Disc level	Nerve root	Dermatome-pain distribution and sensory loss	Motor weakness	Reflex
C1-C2	C2	Posterior occipital headaches, temporal pain	None	None
C2-C3	C3	Supraclavicular, suboccipital and posterior auricular regions	Trapezius, levator scapulae, strap muscles, sternocleidomastoid, diaphragm	None
C3-C4	C4	Infraclavicular and posterior cervical regions, posterior shoulder	Trapezius, rhomboids, levator scapulae, diaphragm	None
C4-C5	C5	Superolateral arm pain	Deltoid, supraspinatus and infraspinatus, biceps	Biceps
C5-C6	C6	Lateral forearm, thumb and index finger	Wrist extensors, biceps, brachioradialis	Brachioradialis (supinator), biceps
C6-C7	C7	Medial scapula, posterior arm, dorsum of forearm, third finger	Triceps, wrist flexors, and finger extensors	Triceps
C7-T1	C8	Shoulder, ulnar side of fore arm, and pain in ring and fifth finger	Finger flexors (flexor digitorum superficialis and profundus, flexor polices longus) lumbricals 3 and 4	None
T1-T2	T1	Axillary and pectoral region, medial arm and	Hand intrinsics, Horner's syndrome	None

**Fig. 39.2:** Cervical dermatomal distribution.

Source: Dvorak J. Epidemiology, physical examination and neurodiagnostics. Spine. 1998;23(28):2663-72.

**Fig. 39.3:** Pain in the scapular region and its corresponding cervical roots.

Source: Tanaka Y, Kokubun S, Sato T, et al. Cervical roots as origin of pain in the neck or regions. Spine (Phila Pa 1976). 2006;31(17): E568-73.

The presentations of other nerve roots are explained in Table 39.2. Upper motor neuron signs such as exaggerated reflexes, increased tone, Hoffman's sign, and finger escape sign along with gait of the patient should always be examined, as cervical myelopathy may be associated with cervical radiculopathy and needs further evaluation.

Differential Diagnosis

There are various conditions around the shoulder and neck region that could produce symptoms mimicking cervical radiculopathy. Meticulous clinical examination along with appropriate investigations would guide the differentiation

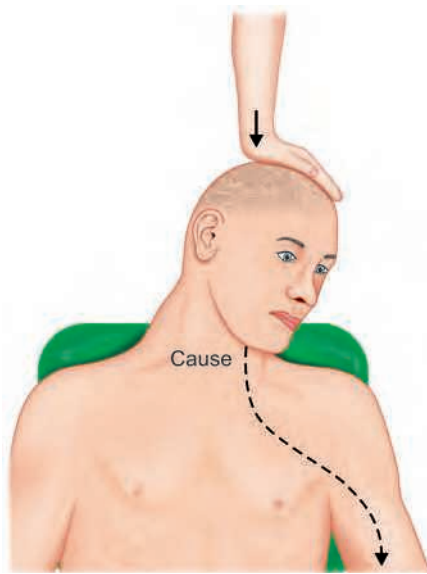


Fig. 39.4: Spurling's test.

of these conditions from cervical radiculopathy. The differential diagnosis and their differentiating features are explained in Table 39.3.

Rarely, cervical radiculopathy might occur in conjunction with other nerve entrapment syndromes, making the clinical diagnosis difficult. Of particular importance is the association of carpal tunnel syndrome that not only causes diagnostic difficulties but also increases symptoms as compression of an axon at one location impairs the axoplasmic flow and makes it more sensitive to compression in another distal location (double crush syndrome).¹³

Diagnostic Modalities

Plain radiographs provide valuable information regarding sagittal balance, reduction of the disc height, presence of uncovertebral osteophytes, loss of intersegmental alignment and instability. However, the poor correlation between clinical symptoms and degenerative changes seen in radiographs and inability to visualize the neural elements restrict the usefulness of plain radiography.¹⁴ Magnetic resonance imaging (MRI) is the gold standard for evaluation of patients with cervical radiculopathy.¹⁵ Careful analyses of both axial and sagittal images can provide considerable information about the cause, severity, and location of the nerve root compression. Use of an oblique series that images perpendicular to the foramen can be useful, as a typical sagittal MRI is not orthogonal to the foramen. Magnetic resonance imaging is valuable in differentiating a soft disc



Fig. 39.5: Davidson's shoulder abduction sign.

from a hard disc or in determining the presence of both. Patients who remain symptomatic even after 4–6 weeks of conservative treatment, patients with significant neurological deficit, signs of myelopathy, or patients with suspicion of other pathologies like tumor, or infection require an MRI. The high frequency of abnormal MRI findings in asymptomatic individuals should also be kept in mind before taking any clinical decision (Figs. 39.6A and B).¹⁶

Computed tomography (CT) has a limited but important role in patients who are claustrophobic and in those with contraindications to MRI. Computed tomography scan is particularly useful to assess foraminal encroachment by osteophytes and in combination with intrathecal contrast (CT myelography) it gives accurate assessment of both the spinal and neural anatomy.¹⁷ Computed tomography myelogram is also indicated in patients with adjacent segment disease who have previous instrumentation in whom metal artifact is a problem. Other than clearly depicting bony causes of central or foraminal stenosis, MRI has the advantage of better delineation of pathology of stenosis with a lower radiation hazard (Fig. 39.7).

Electrophysiological studies, namely nerve conduction velocity and electromyography (EMG), play only an adjuvant role in patients in whom the symptoms and MRI findings do not correlate. Nerve conduction velocity that analyses the amplitude, distal latency, and the conduction velocity is an important tool in differentiating various nerve entrapment syndromes from cervical radiculopathy. Presence of fibrillation potentials and positive sharp waves at rest in EMG is suggestive of muscle denervation. These findings often take 3 weeks to occur after the onset of neural

Table 39.3: Differential diagnosis of cervical radiculopathy.

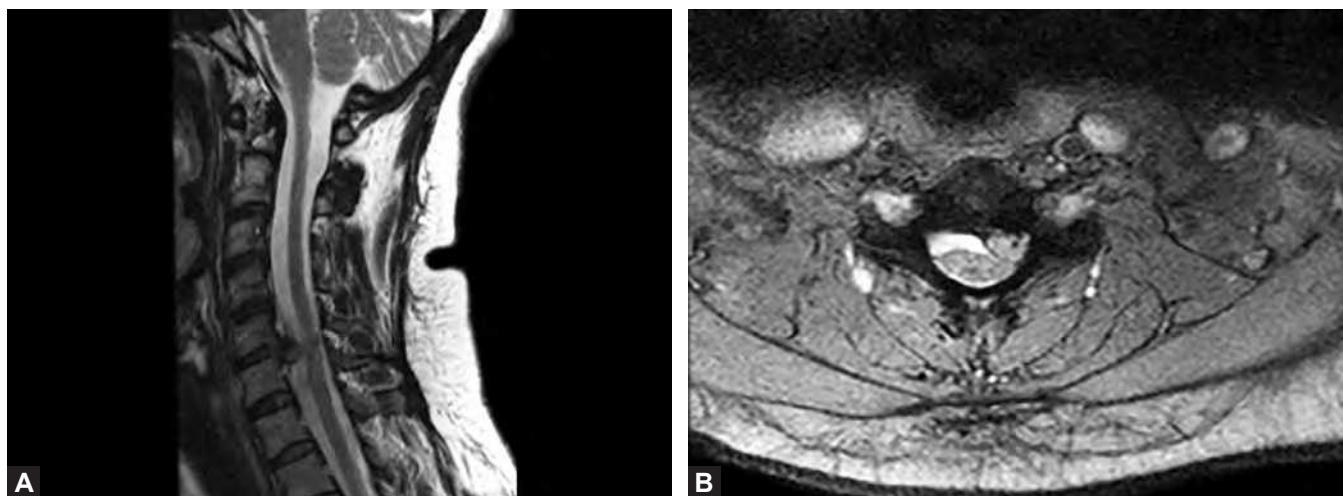
<i>Differential diagnosis</i>	<i>Nerve root mimicked</i>	<i>Differentiating feature of the condition</i>
Rotator cuff tear and other shoulder affections	C5	<ol style="list-style-type: none"> 1. Shoulder abduction might be weak but other muscle groups (biceps) supplied by C5 root not involved 2. Tenderness of shoulder joint with restricted movements 3. Shoulder-specific provocative tests include Hawkin's sign, Open-Can sign and Speed's test 4. Not associated with any sensory component or reflex loss 5. Severe catching pain when the patients' abducts the arm above 90°
Acute brachial plexus neuritis (AKA, Parsonage-Turner syndrome)	C5, C6	<ol style="list-style-type: none"> 1. Severe pain in neck, shoulder, and arm that is followed by marked weakness in C5 and C6 myotome within few days to weeks 2. In cervical radiculopathy, pain and neurological findings occur simultaneously 3. Nerve conduction study might be needed in some cases to differentiate
Suprascapular nerve entrapment	C5	<ol style="list-style-type: none"> 1. Pain in the shoulder and weakness of the shoulder girdle are common complaints. Atrophy of the supraspinatus and infraspinatus muscles seen 2. Not associated with weakness of other C5 innervated muscles such as deltoid, biceps, and pectoralis major
Carpal tunnel syndrome	C6, C7	<ol style="list-style-type: none"> 1. Nocturnal dysesthesia and hypoesthesia present distally only in palmar aspect of hand (first three digits) 2. Weakness and atrophy of thenar and first two lumbricals 3. Phalen's test may be positive and Tinel's sign may be present.
Anterior interosseous nerve entrapment	C8	<ol style="list-style-type: none"> 1. Pain in the proximal forearm 2. Weakness or paralysis of the flexor pollicis longus, the flexor digitorum profundus to the index and long fingers, and the pronator quadratus- positive pinch sign 3. Finger flexors of ulnar two fingers will be normal 4. No sensory loss
Ulnar nerve entrapment—cubital tunnel syndrome	C8	<ol style="list-style-type: none"> 1. Tingling or “pins and needles” sensation in the little and ring fingers 2. Tenderness along the medial aspect of the elbow 3. Positive ulnar Tinel's sign
Thoracic outlet syndrome	C8, T1	<ol style="list-style-type: none"> 1. Intermittent paresthesia in the C8 and T1 region provoked by Roos test (rapid flexion extension of fingers with shoulder abducted to 90° and externally rotated to 90°). C8-T1 radiculopathy is very rare 2. Reproduction of symptoms with rotation of the neck to the contralateral side and tilting of the head to the contralateral side in contrast to cervical radiculopathy where the opposite produces the pain (Spurling's test) 3. Hyperabducting the arm to 180° pulls the components of the neurovascular bundle around the pectoralis minor tendon, the coracoid process, and the head of the humerus aggravating the symptoms of thoracic outlet obstruction, while in cervical radiculopathy hyperabduction relieves the pain (Davidson's test)

injury. Denervation potentials appear sooner in paraspinal muscles and the presence of it differentiates cervical radiculopathy from brachial plexitis.¹⁸ Electromyography can also help identify patients with a double crush syndrome.

NATURAL HISTORY OF CERVICAL RADICULOPATHY

Most studies quoted in the literature regarding the natural course of cervical radiculopathy suggest that the majority

of the patients improve with conservative treatment. In a multicenter trial for cervical radiculopathy, 75% of patients with pain, irrespective of the presence of paresthesia, improved in 4 weeks with conservative care. The use of traction or cervical collar did not influence the outcome. Lee and Turner in their study of 51 patients with cervical radiculopathy observed that 45% of patients had only one episode of pain without any recurrence and only 25% of patients had persistent radicular pain.¹⁹ Heckmann et al. compared conservative and surgical treatment in patients



Figs. 39.6A and B: T2W MR image showing C5-C6 left posterolateral soft sequestered disc herniation in sagittal (A) and axial (B) imaging.



Fig. 39.7: Computed tomography myelogram showing left posterolateral hard disc prolapse.

with primary acute cervical radiculopathy secondary to herniated cervical discs. Sixty-five percent of patients were successfully treated conservatively and only 35% needed surgery.²⁰ In contrast, Gore et al. reviewed conservatively treated patients with cervical radiculopathy and found that 50% had persistent symptoms at 15-year follow-up and stated that, while short-term nonoperative treatment may alleviate symptoms of cervical spondylotic radiculopathy, with long-term follow-up, many patients might have recurrence of symptoms.²¹ There is no literature support for the widespread belief that degenerative cervical radiculopathy might eventually progress to spondylotic myelopathy.¹⁹ There is still a lack of literature regarding

the long-term outcome of patients treated conservatively and studies that have followed up patients with soft and hard disc separately.²²

Goals and Treatment Options

The main objectives in the treatment of cervical radiculopathy are to (1) reduce pain, (2) improve functional status, (3) resolve neurological deficits, and (4) prevent recurrence.

The initial treatment must be planned in such a way as to achieve the above goals. Unless patients have severe intractable pain or significant neurological deficits, a 6–12-week conservative trial of treatment is mandatory. Cervical radiculopathy rarely requires urgent surgical intervention.

Patient Education

All patients must be educated about the natural history of the disease, anatomical considerations, response to treatment, side effects of specific treatments, their expectations during the recovery period, and the indications for surgery. Avoidance of activity that will aggravate pain, maintaining proper posture and neutral positioning of the neck during daily activities, must be emphasized. This will avoid irritation of the nerve root and reduce the intensity of treatment recommended.

The conservative line of management can be classified into noninvasive and invasive modalities. Noninvasive modalities include medication, rest and immobilization, cervical traction, ice/heat therapy, transcutaneous electrical nerve stimulation (TENS), massage therapy, physical

therapy, and alternative medicine. Interventional treatments include cervical epidural steroids and transforaminal or selective nerve root injections.

Medications

Medications used include nonsteroidal anti-inflammatory drugs (NSAIDs), opioids, muscle relaxants, anti-depressants, anticonvulsants, and steroids.

Analgesic medication may be prescribed to reduce pain and improve activity tolerance. First-line medication consists of acetaminophen or an NSAID. Nonsteroidal anti-inflammatory drugs inhibit the enzyme cyclo-oxygenase (COX) and the COX pathway, thereby inhibiting the production of prostaglandins. They act as analgesics in lower dose and as an anti-inflammatory agent in higher doses, thereby addressing the inflammatory component of radiculopathy. The main concern is toxicity related to gastrointestinal (peptic ulcer), renal (acute renal failure), and cardiovascular systems (water retention and hypertension). Patients at high risk are those on long-term treatment, the elderly, those taking concomitant corticosteroids, and patients with pre-existing peptic ulcer disease. Alternative analgesia in the form of opioids, nonopioids, and newer COX-2 inhibitors should be considered in this group of patients. COX-2-selective NSAIDs are highly specific inhibitors that leave the COX-1 pathway undisturbed, thereby not inhibiting the gastroprotective properties.²³ The controversy continues regarding the use of NSAIDs and the increased risk of atherothrombotic events like myocardial infarction and stroke at higher doses. The exact mechanism for this variable increased risk of cardiovascular events with selective COX-2 inhibitors is not clearly understood, but research suggests that it could be related to the extent of COX-2 inhibition by drugs that do not block COX-1 completely.²⁴ Though there is no study comparing the efficacy of NSAIDs over acetaminophen in cervical radiculopathy, there are significant benefits noticed in patients with severe osteoarthritis of the hips and knee.^{25,26} Diclofenac is associated with a 40–60% increase in risk of cardiovascular events compared to nonuse of NSAIDs;^{27,28} however, naproxen has reported to have a relatively lower risk.²⁹

If an acute episode of radiculopathic pain is particularly severe, narcotic medication may be appropriate. The advantages of opioid analgesics over the nonopioid (acetaminophen) and NSAID medications are that they do not have an end organ like hepatic and renal toxicity, respectively. The vast majority of patients readily discontinue narcotics once an acute pain episode has resolved

and there is no ceiling effect. Concerns regarding the risk of respiratory depression and addiction have limited the use of narcotic opioid analgesia in chronic pain. The dose of the opioid can be reduced with combination of acetaminophen that is effective as a multimodal therapy. Previous psychological disorders, major depression, and substance abuse are contraindications for opioid use. Neuropathic pain, however, may be somewhat opioid resistant.

Significant paraspinal muscle spasm can usually be adequately treated with a soft cervical collar. A minority of patients may benefit from a brief trial of muscle relaxants, such as norflex, cyclobenzaprine, or diazepam. Muscle relaxants reduce the paraspinal and trapezius muscle spasm that may worsen the radicular pain symptoms. A meta-analysis of placebo-controlled trial of cyclobenzaprine reported significant improvement in mixed populations of neck and low back pain.²⁴ The most common of these adverse effects are sedation and dry mouth. These medications may, however, have a higher addiction profile than narcotics and treatment should not be prolonged beyond 2 weeks.

In the subpopulation of patients with pain-induced depression, antidepressant medication, such as amitriptyline, may also reduce neuropathic pain. The therapeutic efficacy may also be related to either their inhibitory effect on serotonin and/or epinephrine uptake. The common side effects of antidepressant medication are drowsiness, weight gain, dry mouth, dizziness, constipation, and urinary retention. Their use in an acute setting is questionable but patients who have sleeping difficulty and acute depression may benefit.

Anticonvulsant medications like gabapentin are now widely used to treat neuropathic pain syndromes, including radiculopathy. Several studies have shown the usefulness, efficacy, and improved quality of life with gabapentin. Some of the side effects are dizziness and somnolence. It is recommended to start at a low dose, 100–300 mg/day, and gradually increases until either pain control is achieved or adverse effects occur within the recommended range.³⁰ Pregabalin has been shown in studies to provide equivalent efficacy to gabapentin, however, at much lower doses. Pregabalin at lower doses has a much higher bioavailability and rapid absorption, thereby reducing the dose-related side effects. Monotherapy or add-on pregabalin is associated with substantial pain relief in patients with cervical and lumbar radiculopathy.³¹

The use of oral corticosteroid medications for treatment of acute radiculopathy is controversial. Theoretically, their efficacy is due to a potent anti-inflammatory effect

through inhibition of phospholipase A2 and decrease in arachidonic acid and prostaglandin production on irritated nerve roots. Patients often demonstrate rapid and dramatic reduction in acute pain levels. A tapering dose of methylprednisolone can be given for a period of 1–2 weeks. The toxicity of corticosteroids is limited when these drugs are used for short periods; however, behavioral changes, such as depression and peptic ulceration, can occur. Liberal use of steroids should be balanced with the risk of osteonecrosis particularly in younger patients.

Rest and Immobilization

During the period of acute pain and spasm, a short period of bed rest is thought to reduce the pain by reducing the inflammation around the nerve root and muscle spasm. Instead of absolute bed rest, most authors prefer limitation of specific activities such as hyperextension of neck and rotation of neck to ipsilateral side to prevent foraminal narrowing and pain exacerbation.³² Using a soft cervical collar closed in the front to maintain the neck in slight flexion for a short period of time can be beneficial.³³ A nighttime collar helps maintain proper neck position and limits unconscious neck movements. Although collars have shown good benefit in management of cervical radiculopathy,³⁴ their potential negative effects are weakness and muscle atrophy, promotion of contractures, and psychological dependence.³⁵ Ideally, collars should be weaned off in a period of 2–3 weeks. Isometric neck exercises during this period can reduce muscle atrophy.³⁶ There is no evidence to suggest that using a collar would alter the duration of symptoms or alter the need for surgical treatment.³⁷

Cervical Traction

Traction is thought to relieve pain by enlarging the intervertebral foramina, separating apophyseal joints, relaxing muscle spasm, and reducing intradiscal pressure.³⁸ One study has shown an 81% relief of pain in mild-to-moderate cervical spondylosis, though the patient groups were mixed. Cervical traction may be intermittent, continuous, or sustained and can be applied by manual methods, motorized or pneumatic devices. The usual traction force applied is between 10 and 20 lb for 15–20 minutes with mild neck flexion at 20°. ³⁹ Traction with the neck in extension may worsen the arm pain by narrowing the neural foramen. Suboptimal response during initial traction application or worsening of symptoms often warrants discon-

tinuation. Although cervical traction is widely used, there is little evidence to support its use.⁴⁰

Transcutaneous Electrical Nerve Stimulation

Transcutaneous electrical nerve stimulation uses electrical currents for nerve excitation produced by portable stimulators. Two or more electrodes are placed over the skin and a battery operated unit is used to produce currents at a frequency of 10–50 Hz. The TENS machine can modulate the pulse width, frequency, and intensity of the current required for treatment of pain. Though there is some evidence for the management of low back pain, the literature does not contain enough information to indicate that these devices provide any significant benefit for the treatment of cervical radiculopathy.

Massage Therapy

Massage can relieve painful muscle spasms associated with radiculopathy by increasing cutaneous blood flow, mobilization of tissue, relief of muscle hypertonicity, and reduction of swelling. Although there is a paucity of literature to support its use anecdotally, it can be helpful in the subacute phase when muscle spasm can accompany radiculopathy.

Physical Therapy

Physical therapy has not been shown to alter the natural history of cervical radiculopathy. After a period of rest isometric exercises to strengthen the cervical musculature are instituted. Isometric exercises involve muscle strengthening without painful motion of the cervical spine. However, isometric contraction of local musculature, most often the trapezius, may result in increased loading of the intervertebral discs and exacerbate pain. Aerobic conditioning may also be helpful in relieving symptoms. Aerobic exercise for individuals with cervical spine pain is generally limited to low-impact activities. Stationary bicycling, walking, use of a Stairmaster machine, and other nonimpact aerobic exercises are preferred to avoid jarring the cervical spine. Active range of motion and resistive exercises may be added as the pain improves. It is best for the patient to be involved in a whole-body exercise program with special attention to the shoulder girdle and neck musculature. In cervical disc disease, special attention should be given to the scapular stabilization muscles, including the trapezius, deltoids, latissimus dorsi, and rhomboids. The final step in the rehabilitation protocol is a home exercise program. Postural

education, ergonomics, and lifestyle modifications may also be beneficial in preventing recurrences.

Alternative Medicine

Acupuncture is a treatment in which thin hair-like needles are placed at specific points in the body to prevent or treat illnesses. Stimulating these points is believed to promote the body's natural healing capabilities and enhance its function. It has gained popularity in clinical practice for pain management. One of the principles by which acupuncture works is by stimulating the central nervous system to release neurotransmitters and hormones that dull pain, boost the immune system, and regulate various body functions. While there is anecdotal evidence that acupuncture may be beneficial for cervical radiculopathy, there lacks good clinical evidence to support its use.

INJECTION MANAGEMENT

Injections are an alternative to other noninterventional methods to relieve radicular pain. Cervical epidural steroid injections, transforaminal epidural injections, and selective nerve root injections are good treatment options when patients fail to respond to medication and conservative care. Injections are also a diagnostic tool when there is a mismatch between symptoms and radiologic findings. An injection of local anesthetic and corticosteroids is used in both an epidural and a selective nerve root injection.^{41,42}

Cervical Epidural Steroid Injection

Cervical epidural steroid injections can be performed via an interlaminar or transforaminal route. The cervical transforaminal epidural technique is carried out utilizing an oblique radiologic view of the targeted intervertebral foramen. This view is obtained with the patient in a supine position. The skin is prepared and draped. The C2-C3 foramen is used to count down to the appropriate level to be injected. Once the targeted foramen is identified with fluoroscopy then the skin is infiltrated with 1% lidocaine. A 25G spinal needle is advanced to the posterior-inferior edge of the foramen and slightly redirected into the foramen and advanced a few millimeters. Anteroposterior (AP) and lateral pictures are taken to verify the position. In the AP view, the needle tip should not extend further medially than the midpoint of the adjacent pedicle. Once the position is confirmed 0.5 mL of contrast is introduced under live fluoroscopy; 1–2 mL of 0.5 or 1% lidocaine and 1–2 mL



Fig. 39.8: Oblique views of a transforaminal injection revealing epidural spread.

Source: Wang LH, McKenzie-Brown AM, Hord A. Handbook of Carm fluoroscopy-guided spinal injections. Taylor & Francis Group, LLC; 2006. Chapter 8: Cervical Injections. p. 217.

of corticosteroid are then injected allowing the medicine to cover the nerve root and epidural space (Fig. 39.8).

A cervical interlaminar epidural injection can be performed in the seated, lateral, or prone position. The desired interlaminar space is identified with a fluoroscope. The injection is usually performed in the midline usually in the C7-T1 or the C6-C7 space. The skin is prepped and anesthetized with 1% lidocaine. An 18G or 22G Tuohy needle is inserted into the epidural space using the standard epidural technique. Anteroposterior and lateral fluoroscopic views can be used intermittently to identify the depth of the needle. Once the needle has reached the epidural space, 1–3 mL of nonionic contrast is injected to confirm the spread of dye; 1–2 mL of 0.5 or 1% lidocaine and 1–2 mL of corticosteroid are injected (Fig. 39.9).

Selective Nerve Root Block

Cervical selective nerve root injections are specific to one nerve and are distinctly different than epidurals. They have been reported to relieve pain in 28.6–81% in various series.⁴³ Pain relief was more effective in the first few weeks compared to 6 months.⁴³ A meta-analysis to determine efficacy is difficult because the dose and combination of steroid and local anesthetic use varied. Selective nerve root injections are more commonly used to isolate a specific symptomatic nerve root level as the medication does not reach the epidural space. The technique for a selective nerve root block is very similar to the transforaminal

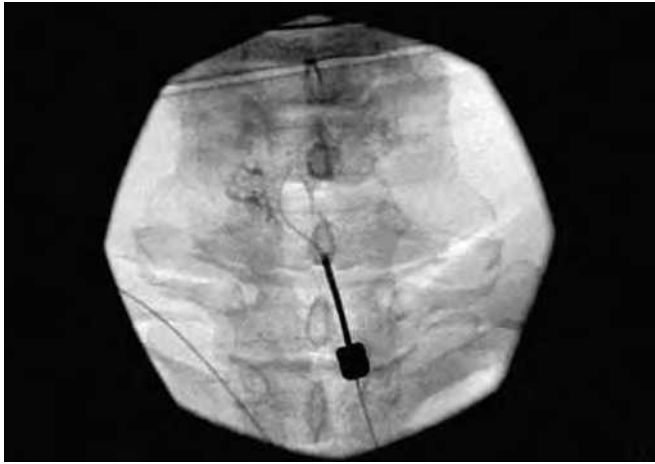


Fig. 39.9: Interlaminar needle placement with a catheter threaded and contrast lateralized to the left side. The needle was inserted at the C7/T1 interspace.

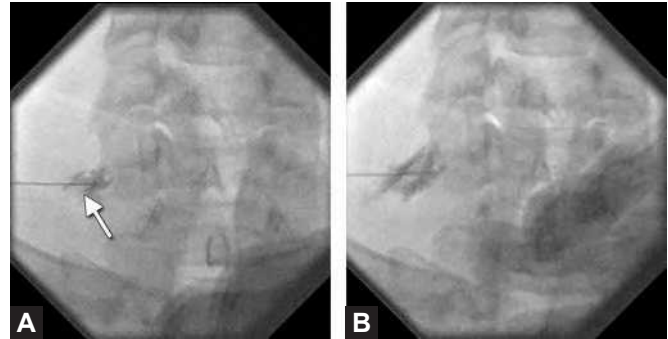
Source: Wang LH, McKenzie-Brown AM, Hord A. Handbook of Carm fluoroscopy-guided spinal injections. Taylor & Francis Group, LLC; 2006. Chapter 8: Cervial Injections. p. 213.

epidural injection except that the needle tip is placed in the more lateral aspect of the foramen. A small amount of contrast is injected, and if it spreads along the nerve root and not into the epidural space 1–2 mL of local anesthetic and steroid is given.

Selective nerve root blocks in the cervical spine have been associated with several neurological complications including vascular injury, cerebral infarction, and spinal cord injury.⁴⁴ Several precautions must be taken to avoid these serious complications. Vertebral artery injection causing cerebral infarction is due to embolization of the particulate steroids injected. Use of betamethasone and dexamethasone rather than methylprednisolone and triamcinolone can help reduce this complication as they are manufactured at smaller particle sizes in suspension form. To prevent direct injury to the cord real time, AP views are advised and the tip of the needle must be located half-way between the medial and lateral border of the lateral mass, as insertion beyond this depth risks puncturing the dura. Caution should also be taken when injecting the contrast although the nonionic monomer radiographic contrast medium, iohexol (Omnipaque 300), is relatively safe (Figs. 39.10A and B).

KEY POINTS

- Radicular pain and sensory disturbance are the most common presentation of cervical disc prolapse that improve most of the time with conservative management.



Figs. 39.10A and B: Cervical nerve root block. (A) Contrast is instilled through the needle to confirm appropriate tip placement and to exclude intravascular location (arrow showing contrast outlining the nerve root). (B) The medication is injected under fluoroscopic guidance to confirm dilution of the contrast.

Source: Blankenbaker DG, Davis KW, Choi JJ. Selective nerve root blocks. *Semin Roentgenol.* 2004;39(1):24–36.

- The C6 and C7 roots are the most common levels to be affected.
- Magnetic resonance imaging is the gold standard for diagnosing and differentiating a soft and hard disc.
- Conservative treatment is multimodal and includes a combination of medical and physical therapy.
- Injection therapy gives good local anti-inflammatory relief for acute radiculopathy

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Surgical Treatment of Cervical Spondylotic Radiculopathy including Anteriorly and Posteriorly Based Procedures

Klaus John Schnake

Snapshot

- » Anterior Cervical Discectomy and Fusion
- » Total Disc Replacement
- » Anterior Foraminotomy without Discectomy (Uncoforaminotomy)
- » Posterior Foraminotomy
- » Endoscopic Techniques
- » Percutaneous Techniques
- » Complications
- » Postoperative Care
- » Prognosis

INTRODUCTION

Cervical radiculopathy is typically caused by disc herniation or spondylotic foraminal stenosis (Figs. 40.1A to C). However, in the degenerative cervical spine, both pathologies may be present simultaneously. Symptoms include radicular arm pain, neck pain, weakness in specific myotome, diminished sensation in specific dermatome, and altered reflexes.¹ The indication for surgery is persistent pronounced pain with a reduced quality of life despite conservative treatment for >12 weeks. In addition, uncontrollable pain and/or neurological deficits may justify surgical treatment at an earlier time. Due to the overwhelming importance of manual dexterity, any sudden or progressive significant reduction of strength in the C6-8 roots may be a consideration for earlier surgery. Depending on the location of the stenosis or disc herniation and accompanying degenerative changes, clinical symptoms can include radiculopathy or myelopathy and justifies surgical intervention.^{2,3} Prior to surgery, patients should have appropriate imaging with MRI or CT scan. Patients should also undergo flexion-extension radiographs to identify instability.

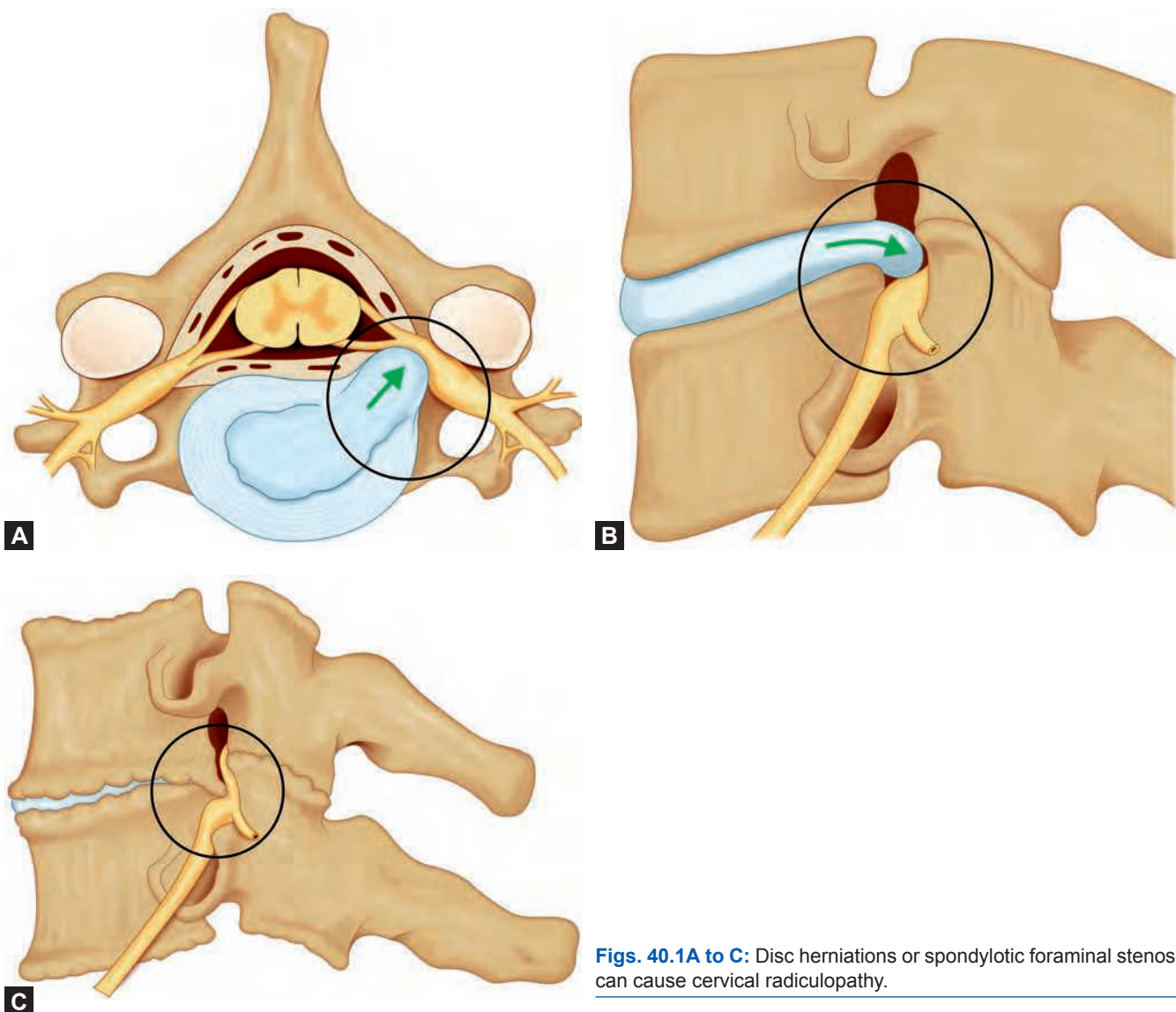
The goal of surgery is to relieve neural compression and stabilize instability. Mechanical compressive pathology may include collapse of the intervertebral disc, sclerosis

of the vertebral endplates, osteophyte formation, facet degeneration, central or uncoforaminal stenosis. The surgical strategy is dependent on the pathological lesion. The long-term goal is a secure and lasting decompression of the neural structures and prevention of recurrent compression.

In the last 60 years, various surgical techniques have been developed. These include the anterior cervical discectomy and fusion (ACDF), anterior cervical discectomy without fusion (ACD), anterior foraminotomy without discectomy, artificial disc replacement (TDR), or posterior laminoforaminotomy. Furthermore, minimal-invasive, endoscopic, and percutaneous techniques have been developed.⁴

ANTERIOR CERVICAL DISCECTOMY AND FUSION

The anterior approach was described in the late 1950s by Cloward.⁵ Smith and Robinson simultaneously described the fusion technique with minimal modification of the original description.⁶ The anterolateral skin incision is typically <3–4 cm. It is our preference to use a horizontal skin incision located at the level of the pathology for one, two, or three level procedures. Four level anterior approaches warrant a vertical incision along the border of the sternocleidomastoid. After incision of the platysma and identification of the sternocleidomastoid muscle as a lateral



Figs. 40.1A to C: Disc herniations or spondylotic foraminal stenosis can cause cervical radiculopathy.

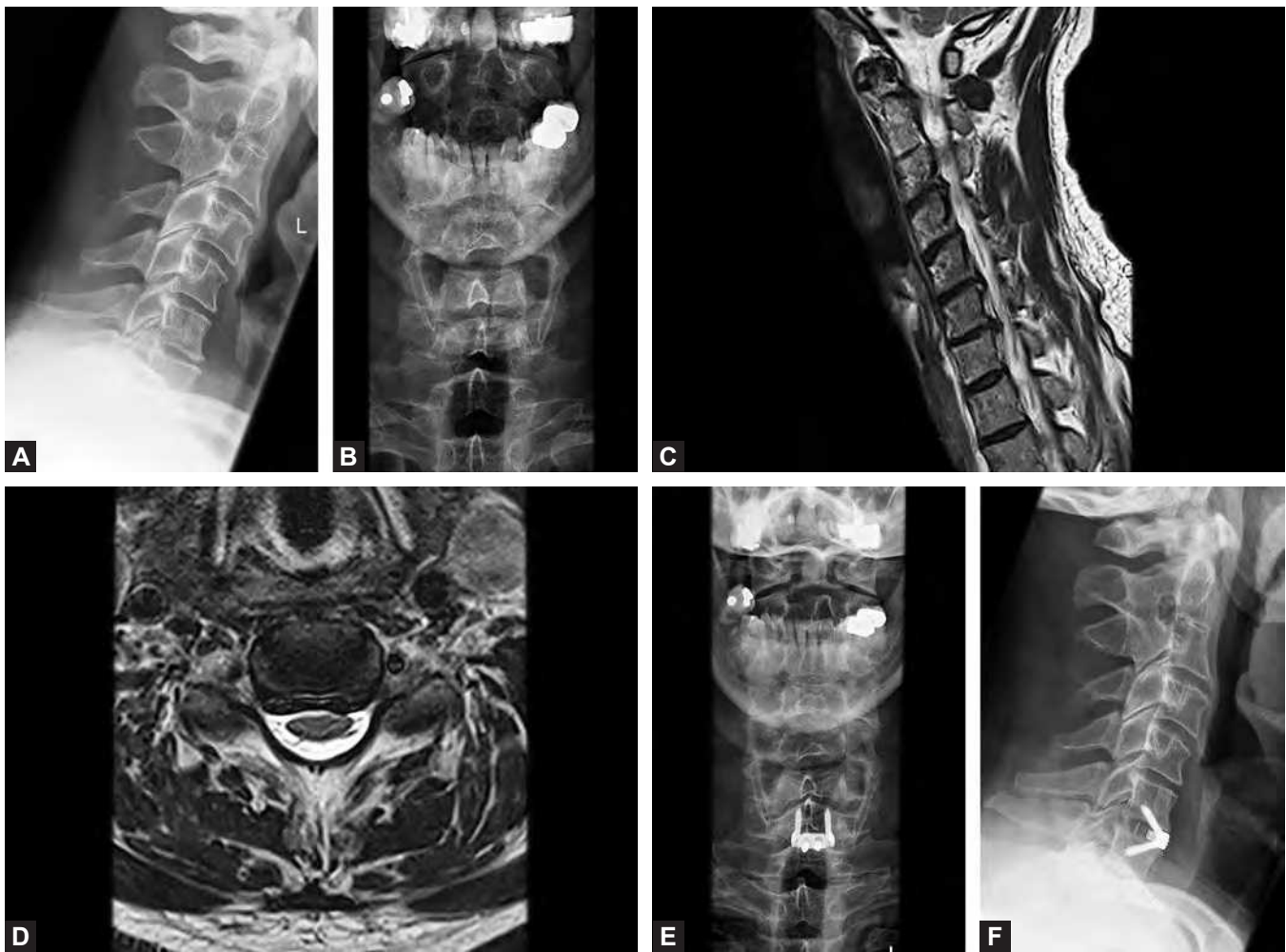
boundary, the index disc space can be located by blunt dissection. Gently lifting the carotid sheath structures and midline airway structures during the approach can facilitate identification of the interval. It should appear as wispy, white fascial tissue that is avascular. The surgeon should be able to palpate the carotid pulse lateral to the approach. At C3/4, a more lateral incision and approach is necessary due to the large size of the midline structures. The longus colli muscles are elevated and a self-retaining retractor is placed after appropriate radiological verification of the correct disc level. To keep the retractors from migrating, we use a small 1 lb weight tied to the retractor on the carotid side, and a 2 lb weight tied to the esophageal side to prevent

anterior migration of the retractors. Following retractor placement, the anterior longitudinal ligament is sharply incised. The anterior part of the annulus and the nucleus is then removed. Distraction of the interspace either with a Caspar-distractor or a Cloward intervertebral body spreader should be performed to facilitate decompression. Microscope or Loupe magnification can be used to help safely resect the posterior annulus and the posterior longitudinal ligament. Central and neuroforaminal decompression can be performed under direct visualization. The herniated disc material can be removed and coexisting osteophytes are resected with Kerrison punches or by using a high speed burr.

In order to restore and maintain segmental lordosis, as well as to achieve a predictable fusion, the majority of surgeons recommend an anterior discectomy with fusion (ACDF). This is a result of earlier studies that describe significant subsidence, kyphosis, and collapse if an anterior discectomy without fusion (ACD) is performed.⁷

Fusion of the segment can be obtained by either using cages or grafts with or without additional plating. The use of a polymethylmethacrylate (PMMA) spacer bears the risk of nonunion and is discouraged.^{7,8} When using iliac crest bone autograft, donor site morbidity must be considered and discussed with the patient.⁹ Cages show bony fusion rates equivalent to those of the iliac crest grafts.¹⁰⁻¹² Differences in clinical outcome between synthetic cage materials (PEEK or titanium) have not been demonstrated.^{13,14} There is ongoing discussion about the possible advantages

of the additive application of a plate or the use of a cage-plate construct. The use of cages without additional security ("stand-alone") carries the risk of subsidence, anterior migration, and formation of a local kyphosis.^{15,16} The use of an additive plate or a cage-plate construct can prevent kyphosis in the later course and may result in better clinical results (Figs. 40.2A to F).^{17,18} It has been shown that in case of two or more levels, the additional use of a plate results in significantly higher fusion rates.¹⁹ On the other hand, some negative side effects of the plates like higher costs, postoperative hoarseness and swallowing difficulties, implant loosening, adjacent segment degeneration, adjacent level ossification disease have to be considered.²⁰ The development of new cage-plate constructs is intended to reduce some of these disadvantages.²¹ It should be emphasized that use of a plate for a single-level



Figs. 40.2A to F: A 59-year-old man with disc prolapse C6/7 with right C7 radiculopathy. Anterior cervical discectomy and fusion with an integrated cage construct (2-year follow-up).

fusion has not been shown to increase union rate but has been shown to reduce progressive kyphosis.²²

The short-, medium- and long-term results of ACDF with fusion rates of >90% and significant improvement of clinical symptoms are well documented.²³⁻²⁵ All other procedures must, therefore, be measured by that standard.

Details of anterior cervical approaches are also discussed in Chapter 36 of this textbook.

TOTAL DISC REPLACEMENT

The implantation of an artificial disc is an alternative treatment option for cervical radiculopathy in the absence of contraindications (Figs. 40.3A to H).²⁶ The maintenance of the mobility of the operated segment is desirable in principle and can be generally achieved with current prostheses. Interestingly, despite maintaining motion at the operative level, there has not been a demonstrated reduction in adjacent segment disease with cervical arthroplasty over fusion.²⁷ Contraindications for cervical disc prosthesis are listed in Table 40.1.^{26,28-30} In general, patients with existing spondylosis and facet joint degeneration are not candidates for cervical arthroplasty. During surgery, care should be taken to resect endplates, posterior bony osteophytes, and the apophyseal ring sparingly, as otherwise a “spontaneous” fusion of the segment may occur.³¹

In order to take advantage of the biomechanical properties of a TDR, placement of the prosthesis in the middle of the vertebral body is indispensable. Intraoperatively, this must be checked with image intensifier in both anterior and lateral views. In the selection of the prosthesis height, care should be taken not to distract the segment excessively. Postoperative intervertebral heights of 5–7 mm are sufficient.³²

The current available data shows equal to better results of cervical TDR in comparison to ACDF in the first 4–5 years after surgery.³³⁻³⁶ However, the lack of long-term results demonstrating superiority of a TDR to ACDF remains to be seen.^{37,38}

Cervical arthroplasty is also covered in Chapter 95 of this textbook.

ANTERIOR FORAMINOTOMY WITHOUT DISCECTOMY (UNCOFORAMINOTOMY)

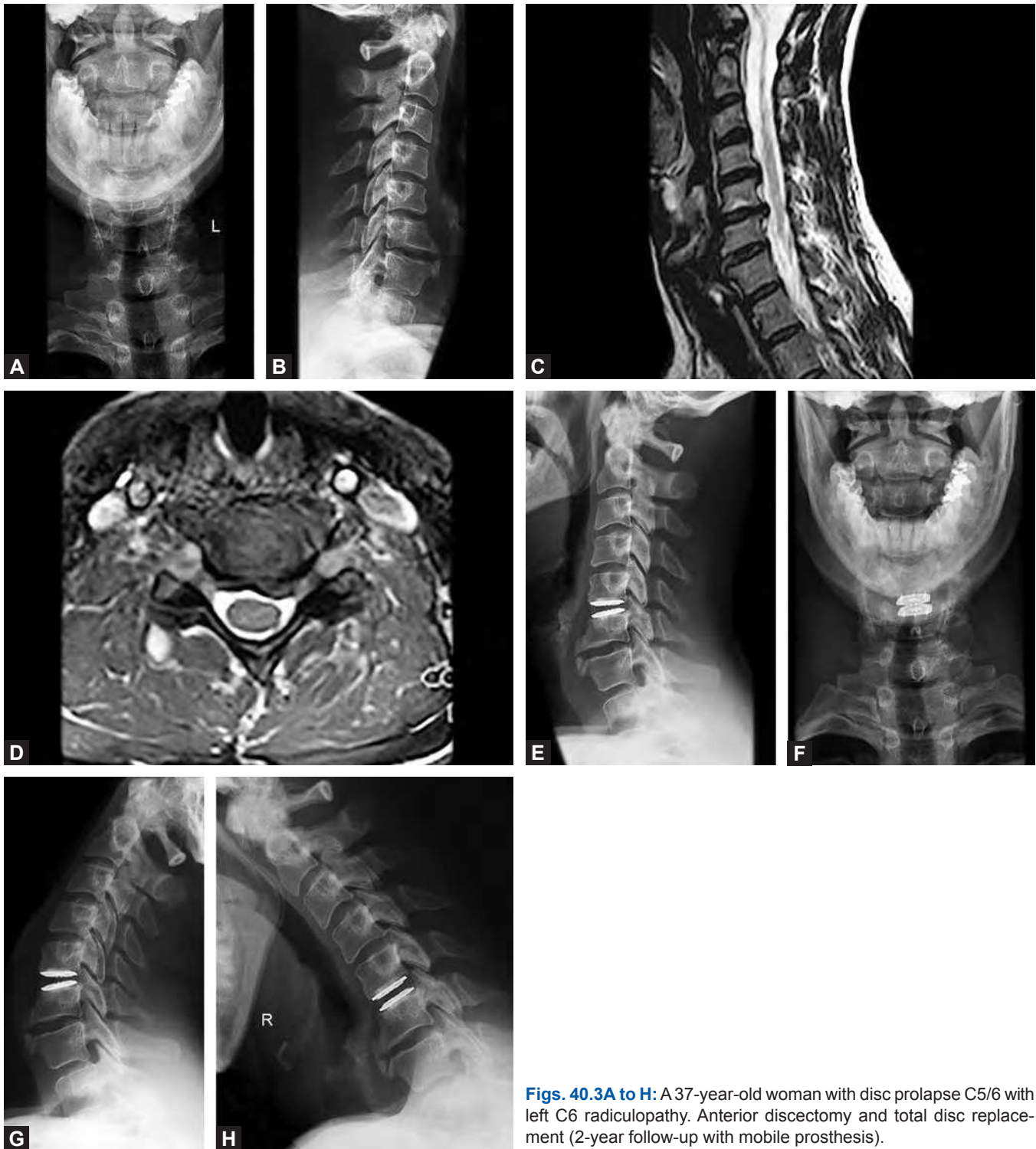
In the setting of neuroforaminal stenosis caused solely by a herniated disc or by osteophytes, anterior uncoforaminotomy is a surgical alternative. This procedure eliminates

the need for an interbody fusion while accomplishing direct removal of the offending lesion. It is also an option for patients who have undergone either or both an anterior and a posterior cervical disc surgery with unsuccessful relief of their radiculopathy.

During this procedure, the medial part of the longus colli muscle is incised and retracted. The uncovertebral joint is then exposed (Fig. 40.4). The foramen is enlarged by access through the uncinat process. Intraoperative visualization is limited significantly with this approach so finding a sequestered disc herniation can be considerably more difficult. In addition, the relative proximity of the vertebral artery and of the sympathetic plexus may lead to injury of either structure. The vertebral artery is directly lateral to the uncovertebral joint and anterior to the nerve root. Prior to attempting this procedure, we recommend carefully reviewing the anatomy of the vertebral artery at the level of surgery, as well as the management of a potential vertebral artery injury. Although the uncinat is not a true joint, disruption of the uncovertebral joint may lead to subsequent autofusion of the operative segment. There is some technical heterogeneity in the procedure description in that some practitioners emphasize resection of the medial portion of the uncovertebral joint and some emphasize resection of the lateral portion of the uncovertebral joint. It is clear that resection of the entire uncovertebral joint destabilizes the spine and creates potential for kyphosis, scoliosis and collapse.³⁹⁻⁴¹

POSTERIOR FORAMINOTOMY

Patients who suffer from isolated radiculopathy caused by a laterally situated soft sequestered disc without longstanding chronic neck pain are ideal candidates for posterior foraminotomies. The intervertebral height should be well preserved, and there should be no associated spinal instability. Other contraindications are significant kyphosis, massive disc herniation compressing the nerve root, and marked spondylosis. Additionally, extensive axial neck pain is considered a relative contraindication to posterior procedure. Through a posterior medial or paramedian access the lamina and the facet joint of the affected segment are exposed, and then opened with a high speed burr (Fig. 40.5). In our practice, we carefully undercut the caudal aspect of the cranial level lamina then undercut the cranial aspect of the more caudal lamina. For instance, at C6/7 we undercut the C6 lamina initially and locate the spinal canal with a nerve hook at that level. Then we undercut the cranial aspect of the C7 lamina working laterally with Kerrison



Figs. 40.3A to H: A 37-year-old woman with disc prolapse C5/6 with left C6 radiculopathy. Anterior discectomy and total disc replacement (2-year follow-up with mobile prosthesis).

rongeurs. Ultimately, the medial aspect of the C7 superior articular process is undercut as that corresponds to the region of highest stenosis. The nerve root is then exposed and carefully mobilized to reach the sequestered fragment.

Fusion of the segment is usually not necessary. Concerns with laminoforaminotomy include the possibility for persistent axial pain and postoperative segmental instability if >50% of the facet has been removed. The clinical

Table 40.1: Contraindications for cervical total disc replacement.^{18,20-22}

Age > 60 years
Significant segmental kyphosis (> 11°)
Functional instability (translation > 2 mm in flexion/extension, vertebral fracture)
Intervertebral disc height < 3 mm
Marked spondylosis of the index segment (osteoarthrosis, facet degeneration)
Long-lasting severe neck pain
Cervical myelopathy
Congenital spinal stenosis (< 10 mm)
Active infection of the cervical spine
Tumor of the cervical spine
Osteoporosis
Ossification of the posterior longitudinal ligament
Systemic infection or metabolic diseases
Known allergy to parts of the implant
Severe adipositas (BMI > 40)
Pregnancy
Alcohol or drug abuse

(BMI: Body mass index).

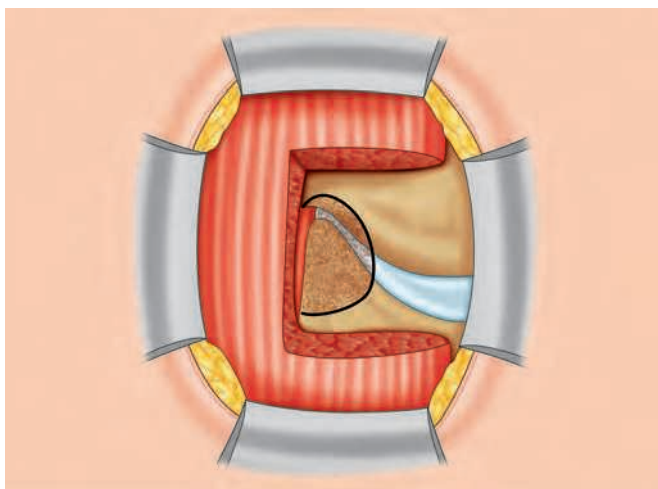


Fig. 40.4: Uncovertebral joint becomes visible after incising the longus colli muscle.

results are similar to those of other procedures with satisfactory to excellent results in 85–90% of cases.⁴²⁻⁴⁴

Minimally invasive posterior cervical foraminotomy is also covered in Chapter 132 of this textbook.

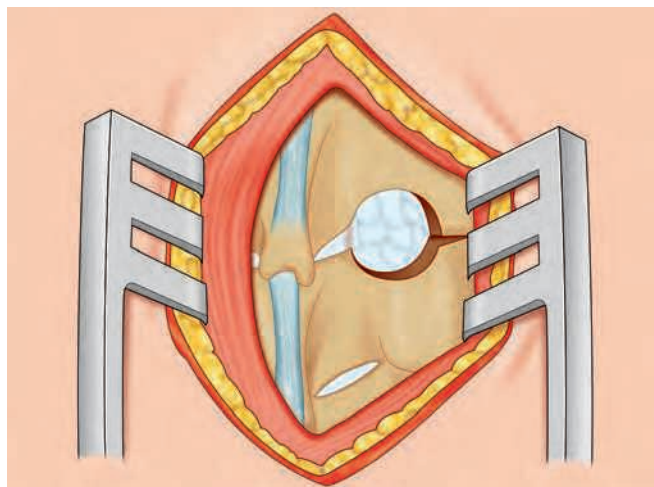


Fig. 40.5: The facet joint is exposed, and then opened with a high speed burr.

■ ENDOSCOPIC TECHNIQUES

Endoscopic techniques exist for both anterior and posterior approaches. Due to limited visibility and working space, only well-localized sequestered herniations can be recovered safely. In principle, it is possible to perform a spinal fusion endoscopically.⁴⁵ Because of a flat learning curve with significant potential complications endoscopic interventions are considered very challenging. Although the reported results are good, superiority to the standard procedures has not been proven. Endoscopic techniques have therefore been established in only a few centers and are carried out by only a few surgeons experienced in this technique.⁴⁵⁻⁴⁸

■ PERCUTANEOUS TECHNIQUES

Percutaneous techniques are typically based on thermal or chemical induced reduction of disc herniations (laser discectomy, nucleoplasty, chemonucleolysis) or percutaneous removal of disc tissue. They are not suitable for the treatment of sequestered disc herniations and should therefore be reserved for contained disc herniations. Although the success rate of these techniques are reported to be >80%, none of these techniques has been proven to be superior in comparison to conservative or surgical therapy.^{13,49,50}

■ COMPLICATIONS

The surgical treatment of cervical spondylotic radiculopathy can be regarded as a safe procedure with a major

Table 40.2: Surgical complications of the cervical spine.⁴³⁻⁵⁵

Overall complication rate 3–5%, severe complications <1%
Overall infection rate 3–6%
Infections due to anterior approach 0.9–1.6%
Injuries of trachea and esophagus <1%
Paralysis of the recurrent laryngeal nerve: transient 6–8%; permanent 0.2–3%
Horner's syndrome <1%
Dysphagia: early postoperative up to 50%; permanent 12–33%
Paralysis of the superior laryngeal nerve 1–2%
Injury of the thoracic duct <1%
Spinal cord injury 1–3%
Epidural hematoma <1%
Postoperative liquorrhea 0.5–3%
Vertebral artery injury <1%
Implant-related complications (dislocation, loosening, subsidence, failure) 1–10%
Pseudarthrosis after fusion <10%

complication rate below 5%.⁵¹ The most frequent complications are caused by implants, followed by nonunions and postoperative dysphagia. For the latter, especially in the early postoperative period rates of over 50% are reported.⁵²

The anterolateral approach generally represents a relatively simple and safe way to reach the anterior cervical spine. From anatomical point of view, the approach should be taken from the left to avoid damage of the recurrent laryngeal nerve. However, several studies have demonstrated no difference in rate of recurrent laryngeal nerve injury between left and right sides.^{53,54} The posterior approach to the cervical spine does avoid the risk of injury to structures in the anterior neck region entirely, but is characterized by an increased risk of wound infection.^{55,56} Furthermore, development of chronic neck pain is possible. Endoscopic and percutaneous techniques carry a particularly high risk for complications and should therefore be used only by experienced surgeons. The possible complications and their frequency of anterior and posterior surgical techniques are listed in Table 40.2.⁵¹⁻⁶³

POSTOPERATIVE CARE

Long term use of postoperative orthotics is rarely necessary.²⁶ In case of an ACDF or TDR, a soft orthosis can be used until wound healing is complete or up to 6 weeks. Isometric

contraction exercises and physical treatment should be carried out until the release of the full range of motion. Thereafter, active muscle training can be started with the objective of restoring range of motion.

PROGNOSIS

The published long-term results of conservative and surgical procedures show satisfactory to good results.^{1,11-13,23-25,36} Ultimately, fusion occurs in many cases due to the natural course or by iatrogenic measures. Long-term results of the motion-preserving procedures are not yet available.

KEY POINTS

- Indications for surgical treatment include neurological deficits and ongoing pain despite 3 months of conservative therapy.
- Radiological findings must match clinical symptoms.
- The aim of surgery is to decompress the mechanically irritated neural structures.
- Anterior cervical discectomy and fusion is the gold standard with good-to-excellent clinical and radiological outcomes.
- Artificial disc replacement is promising as an equivalent alternative to ACDF although long-term data on structural longevity and reduction of adjacent level disease is unknown.

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Cervical Spondylotic Myelopathy: Clinical Evaluation and Nonoperative Treatment

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Snapshot

- » Background
- » Clinical Evaluation

- » Natural History and Nonoperative Treatment

BACKGROUND

Cervical myelopathy represents the clinical syndrome of neurologic dysfunction arising from progressive subacute compression of the cervical spinal cord. Degenerative cervical spondylosis may result in compression of the spinal cord anteriorly secondary to disc-osteophyte complexes and/or posterior longitudinal ligament ossification, and may be potentiated by cervical kyphosis. Posteriorly, spinal cord compression may result from ligamentum flavum hypertrophy, in-folding of redundant ligamentum flavum, and facet hypertrophy, and may be similarly potentiated by cervical extension. Dynamic factors related to position and soft-tissue hypertrophy are more likely to result in symptoms when superimposed upon static congenital cervical stenosis, osteophytes, or bulging intervertebral discs.

The pathophysiology of cervical spondylotic myelopathy (CSM) is complex and likely multifactorial. Anatomic risk factors for the development of CSM are difficult to assess, as the proportion of the population with asymptomatic cervical stenosis is unknown.¹ Mechanical compression likely leads to irritation and inflammation of the neural elements, and this inflammatory cascade may result in demyelination and cellular injury. Anterior compression also likely leads to impaired vascular perfusion of both the spinal cord and nerve roots, likely potentiating the effects of mechanical irritation.² This frequently results in upper motor neuron findings that may be mixed with

a component of radicular pain or weakness (i.e. myeloradiculopathy). Cervical spondylosis is also frequently associated with a degree of segmental instability, and further injury to the spinal cord may occur secondary to altered biomechanics in the setting of pain and impaired proprioception. For the purposes of this chapter, only patients presenting with or diagnosed with myelopathy or myeloradiculopathy will be considered.

The diagnosis of CSM is established by the presence of long tract or upper motor neuron findings on clinical examination that correlate with an appropriate anatomic site of spinal cord compression. The diagnosis is typically confirmed by radiologic findings, either indirectly in the case of plain radiographs or computed tomography (CT) demonstrating altered bony anatomy, or by direct demonstration of intraparenchymal signal changes on magnetic resonance imaging (MRI). In mild cases of myelopathy, the neurologic manifestations may be subtle and diverse making the diagnosis challenging to establish. Symptom progression is often insidious and pain may be variably present. Making the diagnosis of CSM requires careful attention to the patient's history and physical examination. The critical aspect for the treating physician first lies in recognition, as these disease patterns can be confused with a more central process such as multiple sclerosis or a peripheral neuropathy such as cubital or carpal tunnel syndrome.³ In patients who develop cervical myelopathy associated with rheumatoid arthritis, early symptoms such as difficulty with manual dexterity are often missed

as they are attributed to the patient's systemic condition. Although appropriate imaging is mandatory for confirmation of CSM, the presence of overt clinical findings ultimately leads to the appropriate diagnosis. Brain in 1952 was among the first to comprehensively describe the various clinical findings and natural history of CSM.⁴ Clarke and Robinson, 4 years later, went on to further define the range of signs and symptoms in a large series.⁵ Results from both operative and nonoperative management were disappointing; however, this created a basis for an evolving treatment algorithm. In 1972, Nurick published a functional scale, which is still used today, that was able to grade the severity of symptoms and allow for longitudinal comparison for evaluating efficacy of treatment.⁶ Nurick looked at his own series of patients and found that 56% of patients improved with surgery compared to 40% with conservative management. Despite improved characterization of the disease, no clear consensus exists as to what constellation of clinical findings best define a patient with CSM, and moreover, those who will benefit from nonoperative management as opposed to surgical intervention.

CLINICAL EVALUATION

The typical clinical presentation of CSM is that of a patient with subtle gait disturbances and decreased functional dexterity of the hands. Frequently, a patient's family members or close associates may notice abnormalities of gait that have been attributed to other causes. Common hand symptoms include altered sensation that does not follow a peripheral nerve distribution (e.g. not carpal tunnel or ulnar nerve), difficulty button/unbuttoning clothes or undergarments, difficulty with identifying loose change in one's pocket, or difficulty with fine motor tasks such as opening doorknobs and manipulating small objects. More severe presentations will involve frank gait disturbances, motor weakness, and hyper-reflexia with possible spasticity. An individual patient's specific symptoms are dependent on his or her anatomic site(s) of compression, though mixed presentations are common in the setting of longstanding multilevel disease.

History

Cervical spondylotic myelopathy is the most common type of spinal cord dysfunction seen in patients who are >50 years old.⁶ Clarke and Robinson described three modes of progression with myelopathic symptoms over several weeks to several years.⁵ The authors reported on

120 patients with CSM and found that, although 75% of the patients had periods of stable symptoms, the majority demonstrated stepwise deterioration. Of the remaining patients, 20% had slow but steady progression and 5% had initial deterioration of neurologic function followed by long periods with no progression of symptoms. Sadasivan et al. followed 22 patients with CSM and found that all of the patients showed steady and progressive worsening of symptoms over an average of 6 years.⁷ The natural history of CSM suggests that the majority of patients will have progressive neurological stepwise deterioration in the long term.^{2,8-10} While the typical course is one of general stepwise deterioration in function, some patients have no progression in symptoms while others have a rapid decline.

Neck pain is variably present with CSM: Emery et al. reported that 85% of patients recalled some degree of neck pain over time,¹¹ while Crandall et al. reported less than half his patients had neck symptoms.¹² Given the variability, it is likely that this symptom is a consequence of the degenerative changes as opposed to direct compression of the neural elements themselves.

Subtle changes in coordination in the hands are commonly associated with CSM. Patients may initially complain of functional alterations in the hands or simply changes in sensation. The functional changes may be due to lack of coordination or muscle weakness. Fine motor tasks such as writing or buttoning a shirt may become difficult. These characteristic findings ultimately led Ono to coin the phrase "myelopathy hand."¹³ The practitioner must keep this in mind to help differentiate myelopathy from neuropathy or nerve compression syndromes like carpal tunnel syndrome or cubital tunnel syndrome. Voskuhl and Hinton reported on a series of 13 patients with initial presentation of hand numbness, with the majority of these patients describing symptoms in a glove-like pattern.¹⁴ Sadasivan reported 72% of the patients in his series had diminished upper extremity dexterity on initial presentation.⁷

Upper extremity radiculopathy is also common in patients with CSM. This may exist on one or both arms and has been found to occur in up to 40% of cases.¹² The same degenerative changes that may contribute to central stenosis, such as an osteophyte or protruded disc, may also encroach into the neural foramen and cause nerve root compression and myeloradiculopathy.

Perhaps the most common initial finding in patients with CSM is subjective gait instability. Because symptoms are often subtle and insidious in onset, they may not be readily acknowledged by the patient and instead are

often noted by family or friends. Ambulation at night may be especially difficult due to the combination of impaired proprioception and limited visual feedback in low-light conditions. As the dysfunction progresses, a slower pace and wider-based gait are often noted. Ultimately, the use of assistive devices may be needed. Ambulatory dysfunction with a risk of fall is of particular concern in this patient population, as those with severe CSM are at higher risk for acute spinal cord injury with fall, typically presenting as a central cord syndrome.¹⁵

Bowel and bladder dysfunction are also possible with CSM, though these are typically a late manifestation of the disease. Clarke and Robinson reported rates of bladder and bowel dysfunction of 40% and 2.5%, respectively,⁵ while Hukuda's series of 269 patients with CSM demonstrated 15% with bladder and 18% with bowel dysfunction.¹⁶ Urinary urgency, frequency, hesitation, incontinence, and retention are all possible, and fecal incontinence can occur in a small percentage of patients.

Physical Examination

The clinical assessment of CSM begins with the observation of gait along with ease of motion and coordination of movements. Many combinations of muscle weakness and atrophy, sensory changes, and reflex abnormalities of upper and/or lower extremities can occur. Gait abnormalities occur in CSM patients up to 90% of the time. The classical myelopathic gait is often described as broad-based and lacking a smooth, rhythmic motion. While severe alterations in gait may be obvious, subtle deficits may only be elicited through a specific activity, such as heel-to-toe (tandem) walking. Strategies to enhance stability during ambulation and compensate for loss of proprioception often occur. These usually include the widening of one's stance base and shortening of the step length.^{10,17} As neurologic symptoms progress, ataxic type gait patterns can ensue and this can lead to falls and injury as well as the potential need for assistive devices or a wheelchair.

In addition to observation of gait with provocative testing, a thorough neurologic evaluation, including motor and sensory testing, assessment of reflexes and special testing for coordination and balance, must be completed for both upper and lower extremities. Flaccid weakness and hyporeflexia generally occur at or above the level of compression, with spastic weakness and long tract signs occurring below the level of the lesion. Multiple spinal cord tracts may be affected. Motor weakness results from

ipsilateral or bilateral involvement of the lateral corticospinal tracts. Compression of the spinothalamic tract results in contralateral or bilateral loss of pain and temperature sensation. Ipsilateral or bilateral loss of vibratory sensation and proprioception may be present due to dysfunction of the dorsal spinocerebellar tracts. Paresthesias in a dermatomal pattern are indicative of compression of the dorsal roots. Upper extremity signs and symptoms generally occur in a unilateral fashion while the lower extremity signs and symptoms are more often bilateral.^{5,10}

Focused examination of the extremities begins with observation. In the upper extremities, muscle wasting may be present, particularly in the hand. A thorough sensory and motor examination is necessary of all the cervical dermatomes and myotomes, as well as provocative testing of proprioception, vibratory sense, pain, and temperature. Ono et al. reported a 90% involvement of the hand in spondylotic patients with myelopathy.¹³ Two tests useful for examination of the myelopathic hand include the finger escape sign and the grip and release test, and are both indicative of corticospinal tract dysfunction. The finger escape sign is tested by having an individual hold their fingers in an extended and adducted position for as long as possible. A positive sign in a myelopathic patient is when the ulnar-sided fingers begin to flex and abduct within 30 seconds. The grip and release test is performed by having the patient repeatedly form a fist and release it as quickly as possible. A normal response is the ability to perform the action 20 times in 10 seconds. In the myelopathic patient, the action is slow, uncoordinated and often incomplete.¹⁰ Pathologic reflexes of the upper extremities, such as the Hoffman's sign, may also be present in CSM. The Hoffman's sign is elicited by immobilizing the patient's middle phalanx of the middle finger [keeping the proximal interphalangeal (IP) joint extended] and applying a quick stretch to the flexor digitorum profundus (through the distal IP joint). A positive response occurs with a flexion response of the distal IP joint of the thumb and index fingers. Care must be taken in interpreting this finding as this response is present in up to 5% of the general population. Denno et al. described a variation of the Hoffman's sign, termed the dynamic Hoffman's sign.¹⁸ The test is performed three times with the neck in neutral, flexed and extended position, and may be an earlier indicator of cervical myelopathy. The inverted radial reflex may also be indicative of myelopathy. It is elicited by testing the deep tendon reflex of the brachioradialis: a positive response occurs with a depressed brachioradialis response coupled

with a hyper-reflexive long finger flexor response. A positive inverted radial reflex has been shown to be more specific for cervical cord compression than a positive Hoffman's sign.¹⁷ Pathologic reflexes may also be present with compression of the upper cervical region. The pectoralis reflex is assessed by tapping the pectoralis insertion at the deltopectoral groove. It is considered positive if there is a reflexive response of adduction and internal rotation about the shoulder. Watson et al. showed this response to be highly specific for compression at the C3-C4 level.¹⁹ The scapulohumeral reflex has also been described for evaluating upper cervical pathology. The reflex is tested by tapping the spine of the scapula or the acromion in a downward fashion. The test is considered positive if the scapula elevates and/or the humerus abducts. Shimizu et al. showed that all patients in their series with neural compression between the posterior arch of C1 and the caudal edge of C3 had a positive scapulohumeral reflex.²⁰

A comprehensive motor and sensory examination of the lower extremities should also be performed. Lower extremity findings are characteristically bilateral with hyper-reflexia and evidence of unilateral weakness or sensory changes in a dermatomal pattern. Depressed lower extremity reflexes may alert the practitioner to concomitant lumbar pathology. Long tract signs, although not specific to CSM, may be present. The Babinski response is commonly evaluated. This is performed by briskly advancing the pointed end of a reflex hammer along the lateral plantar aspect of the feet from the heel toward the toes. A normal response is curling of the toes, whereas an upgoing great toe is indicative of upper motor neuron involvement. Testing for clonus should also be performed by forcefully dorsiflexing the feet, which can also indicate upper motor neuron pathology. The crossed adductor response should also be tested. This involves tapping the medial femoral condyle on one side of a patient, who is positioned in slight hip abduction. An abnormal response occurs when the contralateral leg adducts reflexively. Harrop et al. showed this response to be present in approximately 75% of myelopathic patients.²¹

Coordination testing may also reveal evidence of CSM. The Romberg's test is often used to assess subtle deficits in balance. The patient stands with their arms forward flexed and supinated with their eyes closed. A loss of balance is considered a positive Romberg's test and can be indicative of posterior column dysfunction. The inability to perform rapid alternating movements such as

pronation and supination of the forearms is indicative of dysdiadochokinesia, again consistent with posterior column involvement. Finally, the jaw-jerk reflex can be tested. Although this is not a test for cervical myelopathy, it can be used to differentiate cervical versus cranial pathology. It is performed by tapping the chin with a reflex hammer. A pathologic response occurs when the jaw reflexively contracts, indicating possible supratentorial involvement.

There is increasing recognition that a subset of patients presents with tandem stenosis, which is typically described as simultaneous cervical and lumbar stenosis.^{22,23} The presentation of tandem stenosis can be a diagnostic challenge, as the effects of lumbar stenosis may mask the physical findings (i.e. hyper-reflexia) of the cervical stenosis. A detailed history is important, and in the patient presenting with lumbar stenosis, a history that elicits upper extremity symptoms merits consideration of cervical spine MRI.

Radiologic Evaluation

Plain Radiography

Anteroposterior, lateral, flexion, and extension plain radiographs of the cervical spine are routinely obtained for evaluation of the patient with CSM. Nonspecific signs of age-related spinal degeneration are typically observed, such as loss of disc space height and osteophyte formation. One should pay particular attention to the ratio of the sagittal diameter of the spinal canal relative to the diameter of the corresponding vertebral body, which typically is approximately 1.0 (Fig. 41.1). Pavlov et al. posited that a mean ratio of less 0.8 is suggestive of congenital cervical stenosis and a subsequent predisposition to spinal cord injury with minor trauma or degenerative changes.²⁴ Computed tomography images should also be assessed for possible signs of ossification along the posterior longitudinal ligament. Overall cervical alignment should be noted, as well as range of motion with flexion and extension. Careful attention should also be paid to any findings of segmental instability on flexion-extension views.

Magnetic Resonance Imaging

Magnetic resonance imaging has become the preferred modality for assessing the neural elements and surrounding soft-tissue structures. The typical sagittal diameter for the spinal canal is generally 17 mm between C3 and C7 and the average sagittal spinal cord diameter is 10 mm.²

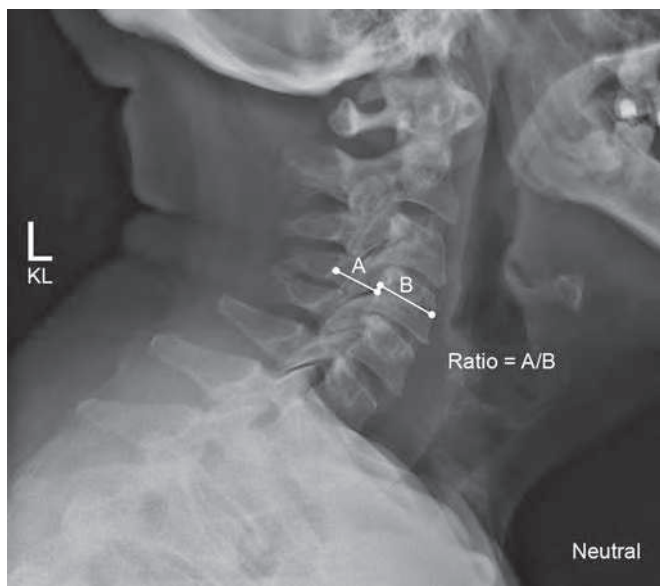


Fig. 41.1: Lateral X-ray of the cervical spine demonstrating the Pavlov, or Torg, ratio measurement.

Relative cervical stenosis is present at sagittal diameters <13 mm, and absolute stenosis is present at diameters <10 mm.² On T2-weighted images, spinal cord irritation may present as an area of hyperintensity, termed myelomalacia (Fig. 41.2). If the corresponding regions are also dark on T1-weighted images, this may represent demyelination and portend a negative prognosis. It is hypothesized that the absence of low-signal changes on T1 may indicate that the damage is reversible.²⁵⁻²⁸ The transverse area of the spinal cord should also be assessed in addition to the degree of compression on sagittal images. Cross-sectional area of <30 mm² has been associated with worse prognosis in CSM.²⁵

Computed Tomography

Computed tomography scanning provides better visualization of the bony elements than MRI and is a complementary study, particularly for surgical planning. Ossification of the posterior longitudinal ligament is best visualized on CT. However, CT without contrast is suboptimal for visualizing the neural elements. Computed tomography with myelography provides good evaluation of intrinsic spinal cord compression, and may offer improved visualization of extrinsic compression of the nerve roots at their takeoff from the spinal cord. This modality may also be especially useful in cases where artifact from prior instrumentation precludes effective imaging with MRI.



Fig. 41.2: Sagittal T2-weighted magnetic resonance imaging of a patient with multilevel cervical stenosis in the setting of degenerative disease. Note the T2-signal hyperintensity lesion consistent with myelomalacia.

Differential Diagnosis

Due to the significant variability in the initial presentation of CSM, careful consideration must be given to other systemic or central nervous system processes capable of producing similar manifestations, as well as peripheral entrapment syndromes and/or coexisting compressive pathology in other regions of the spine. Careful attention to subtle complaints or symptoms that may seem inconsequential can assist in directing the clinician in decision making, physical examination, and obtaining advanced imaging studies that ultimately lead to the diagnosis. Examination of the extremities and/or electromyography with nerve conduction studies may help identify sites of peripheral nerve compression, resulting in seemingly-radicular pain, weakness, or atrophy. Central nervous system demyelinating disorders, such as multiple sclerosis and amyotrophic lateral sclerosis, may result in subtle but progressive neurologic findings, mimicking early stages of CSM. Movement disorders, such as Parkinson disease and Huntington disease, may also produce gait instability and difficulties with fine motor tasks. In addition, early mild cognitive impairment or dementia may impair a patient's awareness of symptom progression. Given the age-related nature of CSM, these conditions are commonly coexistent. Even in the presence of myeloradiculopathy with anatomically corresponding degenerative changes, the presence

of systemic or neurodegenerative disorders may affect the patient's prognosis with or without surgical intervention.

NATURAL HISTORY AND NONOPERATIVE TREATMENT

There is currently no noninvasive therapy that can arrest the progression of the degenerative changes leading to CSM. As such, the primary role of nonoperative treatment in CSM is to provide symptomatic relief of neck or radicular pain, and to maintain overall health and functional status. The true natural history of myelopathy is controversial, with the predominance of the literature comprised of retrospective case series. While many authors report a natural history of progressive neurologic decline with observation/medical treatment,^{15,29} other series have suggested that after initial decline there is a plateau that may not progress in mild cases.^{6,9} Even if a progressive decline in neurologic function over time is predicted, it is uncertain whether the relative risks of surgery outweigh the risks of disease progression in elderly patients with relatively mild symptoms. While risk factors such as age, radiologic findings, or disease severity have been examined, no consensus exists regarding their predictive value for CSM progression.

Medical management options for CSM include cervical orthosis, anti-inflammatory medications, corticosteroids, cervical injections (epidural, selective nerve root block, or facet), cervical traction, and narcotic or non-narcotic analgesics. The role of a cervical orthosis is to immobilize and stabilize the spine. The hypothesis is that the load sharing of the orthosis may alleviate axial neck pain, and the stabilization of the spine may alleviate spinal cord symptoms occurring secondary to dynamic compression (e.g. Lhermitte's sign). Patients with predominantly anterior pathology in the setting of posterior disc bulges and/or endplate spurring may benefit from immobilization in neutral or slight extension, whereas patients with predominantly posterior compression in the setting of infolding of the ligamentum flavum may benefit from immobilization in a slight degree of flexion. However, there is simply no substantive data regarding nonoperative trials that isolated cervical orthosis as a treatment variable for CSM. In the majority of patients, cervical orthoses are of limited morbidity, particularly if removed when eating and/or sleeping, although prolonged use may result in pressure ulcers of the occiput or upper cervical spine in elderly or incapacitated patients.³⁰ In addition, prolonged orthosis wear may result in deconditioning of the cervical musculature.

Nonsteroidal anti-inflammatory medications may alleviate axial neck pain in spondylotic patients via both an analgesic and anti-inflammatory effect. Nonsteroidal anti-inflammatory drugs (NSAIDs) are hypothesized to potentially alleviate myeloradicular pain by modulating the inflammatory cascade that is hypothesized to play a role in radiculopathy. There is a paucity of published literature on the role of NSAIDs in myelopathy. Particularly in the elderly population, NSAIDs may be associated with significant medical complications, and there is increasing recognition of potential cardiovascular side effects.³¹ Steroid injections (either epidural or selective nerve root) have numerous reports in the management of cervical radiculopathy. However, in the setting of myelopathy with spinal cord compression, the role of epidural injection is highly controversial and generally not recommended. There are no studies examining steroid injection or oral steroids as an independent variable for management of myelopathy.

Neck exercises (either self-directed or under the guidance of a trained physical therapist) to strengthen the neck muscles may be beneficial for the management of axial neck pain arising from cervical spondylosis. Cervical manipulation should not be performed in the setting of spinal cord compression with myelopathy.

There are few studies directly comparing operative to nonoperative management for treatment of CSM. Instead, prior studies consist primarily of retrospective observational case series with heterogeneous nonsurgical treatment. More recent studies have applied validated clinical grading criteria in an attempt to systematically assess for disease progression with nonoperative management. Matsumoto et al. described a nonoperative treatment regimen for mild myelopathy from cervical disc herniation consisting of 8 hours of daily cervical immobilization for 3 months, followed by intermittent orthosis use for another 3 months.³² The authors observed significant improvements in Japanese Orthopaedic Association (JOA) scores in 17 of 27 patients (59%). The remaining 10 patients demonstrated disease progression and ultimately underwent surgical intervention. In a subsequent study, the authors examined a larger series of 52 patients with cervical myelopathy due to CSM, ossification of the posterior longitudinal ligament, or disc herniation.³³ Nakamura et al. evaluated a variety of nonoperative treatments, including cervical orthotic immobilization, as halter traction, casting, and Crutchfield traction, in a series of 64 patients treated over 6 years.³⁴ Improvements of at least one

JOA grade were noted in the upper extremity in 55% of patients, and in the lower extremity in 57%, with worsening noted in only 3%. A subsequent long-term analysis over a mean of 6 years revealed that 34 of 53 (64%) maintained their functional status, while 19 (36%) deteriorated necessitating surgical intervention. Shimomura et al. reported a prospective cohort of 70 patients with mild CSM (JOA grade ≥ 13) undergoing a nonoperative treatment regimen consisting of 2 weeks of hospitalization with traction 8 hours per day followed by activity modification at home to minimize risk of fall.³⁵ Of the 56 patients (80%) included after final follow-up at 36 months, no statistically significant decrease in JOA scores was observed; however, 11 patients underwent surgical intervention on the basis of subjective deterioration. Risk factors for deterioration, including age, gender, radiologic developmental or dynamic factors, and abnormal T2-weighted signal on sagittal MRI, were evaluated. The authors concluded that non-surgical treatment of mild CSM produced acceptable outcomes, but that a site of circumferential compression seen on MRI was a risk factor for subsequent deterioration.

Several groups have attempted to directly compare outcomes with surgical and nonsurgical treatment of CSM. Sampath et al. performed a subgroup analysis of 62 patients with CSM from a larger nonrandomized series comparing surgical and nonsurgical interventions for a variety of degenerative conditions of the cervical spine. Nonsurgical therapy included bed rest, bracing, and physical therapy.³⁶ Mean follow-up time was 11 months, with only 43 (69%) of patients available for telephone interview at final follow-up. The surgical group achieved mild improvements in neurologic status compared to slight worsening in the nonsurgical group, and both groups demonstrated equivalent improvements in pain and satisfaction, though none of these changes achieved statistical significance. Further analysis of work and social components of functional assessments revealed statistically significant improvements in the surgical group, though these specific measures have not been externally validated. Kadanka et al. reported the results of a 10-year, prospective randomized trial of operative versus nonoperative management of CSM in a cohort of 64 patients with mild or moderate disease (mean JOA score ≥ 12).³⁷ Outcome measures included a modified JOA grading system and a 10 m walk time. Video assessments of patients performing activities of daily living were also performed, with grading by both blinded observers and the patients themselves. Of the 47 patients (73%) completing the 3-year follow-up period,

no statistically significant differences were seen between surgical and nonsurgical treatment groups with regard to any of the above outcome measures.

CONCLUSION

Cervical spondylotic myelopathy is a multifactorial disease process with an insidious onset and nonspecific symptoms that frequently lead to a delay in diagnosis. The natural history of CSM is generally that of stepwise decline in neurologic function, though extensive disease may increase the likelihood of catastrophic neurologic injury with otherwise minimal trauma. Risk factors for disease progression may include greater severity on presentation in combination with circumferential compression on imaging, though it remains difficult to predict a given individual's disease course on the basis of factors such as age, comorbidities, functional status, or imaging characteristics. For patients with mild or moderate symptoms, or for those in whom surgical treatment may be medically high risk, nonoperative treatment modalities such as analgesia, intermittent immobilization, or physical therapy may be reasonable options for symptomatic relief, though these are unlikely to modify the disease course. The decision to pursue medical or surgical treatment must be pursued on a case-by-case basis, incorporating the patient's specific complaints, life expectancy, quality of life, and perioperative risk factors. Additional randomized, prospective studies are needed to identify patients with CSM at risk for disease progression as well as those who may benefit most from early surgical intervention.

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Anteriorly Based Surgical Treatment of Cervical Spondylotic Myelopathy Excluding Ossification of the Posterior Longitudinal Ligament

Toshitaka Yoshii, Atsushi Okawa

Snapshot

- » Surgical Rationale
- » Preoperative Imaging Studies
- » Decision-making regarding the Surgical Approach: Anterior or Posterior
- » Preoperative Planning
- » Complications

The anterior cervical discectomy and fusion (ACDF) is an effective method for treating patients with a variety of degenerative and post-traumatic conditions of the cervical spine. The goals of ACDF include pain relief, removal of neural compression, restoration of stability, and restoration or maintenance of disc height, foraminal space, and spinal alignment.¹⁻⁴

The anterior approach was developed in the 1950s; Dereymaeker and Mulier⁵ and Smith and Robinson^{6,7} introduced the currently common technique of ACDF. Cloward⁸ described a variation of the procedure using a bone dowel as opposed to a block of bone. In 1960, Bailey and Badgley described a fusion technique for patients with neoplasm and instability involving onlay strut grafts.⁹ Since then, an ACDF has been used to successfully treat cervical stenosis resulting from herniated discs, spondylosis, or ossification of the posterior longitudinal ligament (PLL). In the setting of multilevel spinal cord compression, various anterior decompressive options exist, including multilevel ACDF, corpectomy, and hybrid procedures. In multilevel ACDFs, neurological recovery is high¹⁰ with the consequence of decreasing union rates with an increasing number of levels treated.¹¹

SURGICAL RATIONALE

The prognosis for patients with cervical myelopathy is variable although most patients with cervical spondylotic myelopathy (CSM) experience a stepwise progression of their neurological dysfunction.^{12,13} Nonoperative management, including immobilization and periods of bed rest, has the potential to improve neurological symptoms.^{12,14,15} The majority of patients presenting with cervical myelopathy do not experience spontaneous improvement and instead deteriorate over time. Alternative therapies, such as epidural steroid injections, physical therapy, and non-steroidal medications, have not been shown to alter the natural course of the disease.¹² Manipulation should not be performed for the patients with CSM because neck extension can cause narrowing of the spinal canal.^{12,15} Several studies investigating patients treated conservatively have shown that approximately 26–50% of patients deteriorate neurologically over time.^{12,14,16,17} It is reported that 5% of patients deteriorate quickly, 20% have a gradual but steady decline in function, and 70% experience a stepwise progression of their symptoms with variable periods of quiescent disease.¹²

Nonetheless, several studies have reported that surgery can alter the natural history and change the prognosis of patients with CSM.^{18,19} Neurological improvement was seen in >90% of patients following either anterior or posterior decompression surgery, with neurological recovery ranging from 47% to 100%.²⁰ Recently, a prospective multicenter nonrandomized comparison of operative and conservative treatments for patients with CSM was reported.²¹ In this study, patients treated conservatively had significant worsening of their activities of daily living with progression of neurologic symptoms, whereas patients treated surgically experienced significant improvement in their functional status and neurological symptoms. Optimal results can be obtained when surgery is performed within 6 months to 1 year after the onset of symptoms in patients with mild myelopathy.²²

PREOPERATIVE IMAGING STUDIES

Patients with suspected cervical myelopathy undergo anterior-posterior, lateral flexion extension, and oblique X-rays. Radiographs can reveal spondylotic changes, such as narrowing of the disc space, osteophyte formation, listhesis, and narrowing of the osseous canal. If the sagittal diameter of the spinal canal is 12 mm or less, there is an increased risk of developing myelopathy.²³ The sagittal alignment of the cervical spine is an important factor for deciding on the surgical approach. Flexion-extension X-rays are necessary to evaluate ankylosed and unstable segments.¹⁵ Magnetic resonance imaging (MRI) is a useful modality for evaluation of the spinal cord.^{24,25} Magnetic resonance imaging demonstrates various compressive factors of the spinal cord, such as disc herniation, hypertrophy of the flavum, and PLL. Spinal cord compression can be assessed on both axial and sagittal images. High-intensity cord changes on T2-weighted images are often seen in patients with cervical myelopathy. Low-signal intensity on T1-weighted images is associated with poor prognosis for neurological recovery.²⁶

A conventional myelogram in flexion and extension is utilized to assess the dynamic factor in spinal cord compression.²⁷ A computed tomography (CT) myelogram provides information regarding the bony compressive factors, such as osteophytes and ossified PLL.²⁸ The computed tomography (CT) myelogram images are also useful in the planning of either anterior or posterior surgery.

DECISION-MAKING REGARDING THE SURGICAL APPROACH: ANTERIOR OR POSTERIOR

The choice of either an anterior or a posterior procedure for decompression of CSM is based on multiple factors, such as the location of the compressive pathology, the extent of the degenerative process, the sagittal alignment of the cervical spine, motion preservation, the presence of neck pain, previous operations, and the patient's age and medical conditions.²⁹⁻³¹ Generally, for cases in which the compressive pathology is ventral to the spinal cord, the majority of surgeons prefer an anteriorly based procedure.^{32,33} An anterior approach allows direct removal of the compressive pathology without manipulation of the cord. When kyphotic sagittal malalignment is present, anterior procedures may serve to improve cervical lordosis. The intervertebral arthrodesis may also have an effect on reducing pain arising from the spondylotic motion segment. Fusion of three or more motion segments is associated with a higher nonunion rate and graft-related problems when compared to one- or two-level procedures.^{11,34,35} For patients with greater than three levels of compression, a posteriorly based procedure such as laminectomy/fusion or laminoplasty is preferred.^{29,30,36} Posterior decompression and fusion is an option for patients with kyphosis,³⁷ although high complication rates associated with multi-level posterior fusions are reported.^{38,39} On the basis of the results from a systematic review comparing anterior and posterior procedures, anterior surgery had better clinical outcomes but also had more complications during the early postoperative stage.⁴⁰ At the middle to late stage, posterior procedures had similar clinical outcomes and complication rates to anterior procedures for patients with CSM. We previously conducted a prospective study comparing the anterior and posterior approaches for the treatment of CSM, and we reported that the anterior procedure provided a significantly better improvement of neurological symptoms, particularly in regards to improvement of the upper extremity motor function.⁴¹ We further evaluated the patients with poor outcomes following a posterior approach, and we found that the presence of a residual anterior compressive factor of the spinal cord after surgery can cause an insufficient decompression that is associated with poor outcomes.⁴² This residual anterior compressive factor may be predicted preoperatively by measuring the

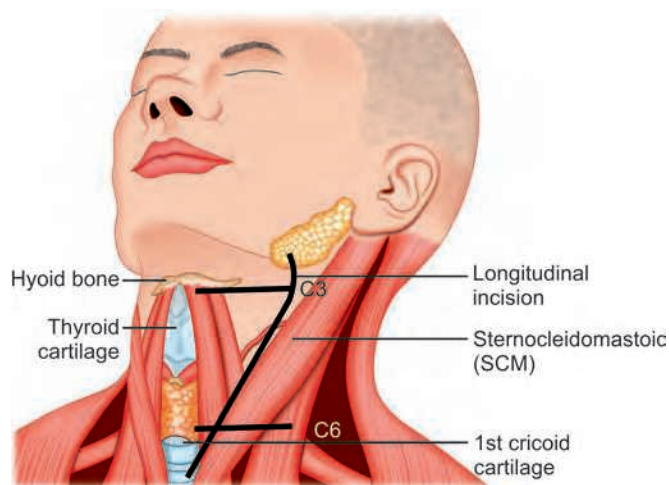


Fig. 42.1: Surface landmarks for skin incisions: the hyoid corresponds to C3, the thyroid cartilage to C4-C5, and the cricoids to C6. An oblique skin incision may be used to fuse three segments or more.

distance between the anterior compressive factor and a midsagittal line connecting the midpoints of the spinal cord at C2 and C7 on MRIs taken before surgery.⁴³

PREOPERATIVE PLANNING

It is critical to evaluate a patient's preoperative respiratory function, as latent preoperative disorders may become symptomatic postoperatively secondary to retropharyngeal edema. Although smoking cessation at least 4 weeks before surgery has been shown to reduce the occurrence of perioperative respiratory and wound complications.⁴⁴ Patients should quit smoking entirely no later than 3 months before anterior cervical surgery because smoking delays bony union. Additionally, preventing provocation of symptoms (e.g. radiating pain to the arm in an extended position) is an important preoperative test for avoiding neural injury during surgery due to incorrect positioning of the neck. In highly stenotic patients, consideration should be taken to use spinal monitoring of transcranial motor-evoked potentials and somatosensory-evoked potentials.⁴⁵⁻⁴⁷

Procedure

The surgery is performed under general anesthesia. A roll placed lengthwise between the scapulae extends the head and neck. Excessive extension of the cervical spine is avoided when preoperative provocative symptoms are positive.

It is our preference to use a left-sided approach due to the more predictive course of the recurrent laryngeal nerve in the tracheoesophageal groove. However, literature suggests that the incidence of recurrent laryngeal nerve injury is not clinically significant when comparing a right- and left-sided approach. A transverse incision is made anterior to the appropriate interspace starting at the midline and extending laterally 4–6 cm. The skin incision level can be estimated from subcutaneous landmarks corresponding to the adjacent vertebrae. The hyoid corresponds to C3, the thyroid cartilage to C4-C5, and the cricoid to C6. An oblique skin incision may be used when three segments or more are being fused (Fig. 42.1).

The dissection is carried through the subcutaneous tissue to the platysma. The superficial cervical fascia is incised, and the interval between the trachea and the esophagus medially and the carotid sheath laterally is separated. The trachea and esophagus are retracted medially to expose the prevertebral cervical fascia overlying the bodies of the cervical vertebrae and the longus colli muscles (Fig. 42.2). Bilateral longus colli muscles are retracted, and retractors are set up carefully on these edges to avoid injury to the sympathetic plexus, esophagus, trachea, and carotid sheath (Fig. 42.3). Operating loupes with directed light or a microscope are used for the discectomy. The disc material is removed roughly with a pituitary rongeur, pituitary forceps, or a curette until the annulus becomes visible. The disks should be sufficiently curetted as far as the bilateral uncovertebral joints ensure accurate canal width and a symmetric decompression. This also ensures maintenance of the correct midline of the vertebral column during surgery. The cartilaginous endplates are removed from the superior and inferior surfaces of the disc space (Fig. 42.4). The posterior rims of the vertebral bodies are carefully trimmed to expose the posterior annulus and PLL. Osteophyte resection is performed by further trimming upward and downward from the posterior rims using a diamond burr (Figs. 42.5A and B). If needed, the PLLs are incised to expose the dura. After removal of the intervertebral disk, the upper and lower vertebral bodies are fused using a variety of graft materials, such as iliac crest autografts, fibula autografts, allografts, cages, and ceramics. Anterior plating is used to prevent graft dislodgment and to enhance the fusion rate. The wound is closed with absorbable sutures and sterilely dressed (Figs. 42.6A and B).

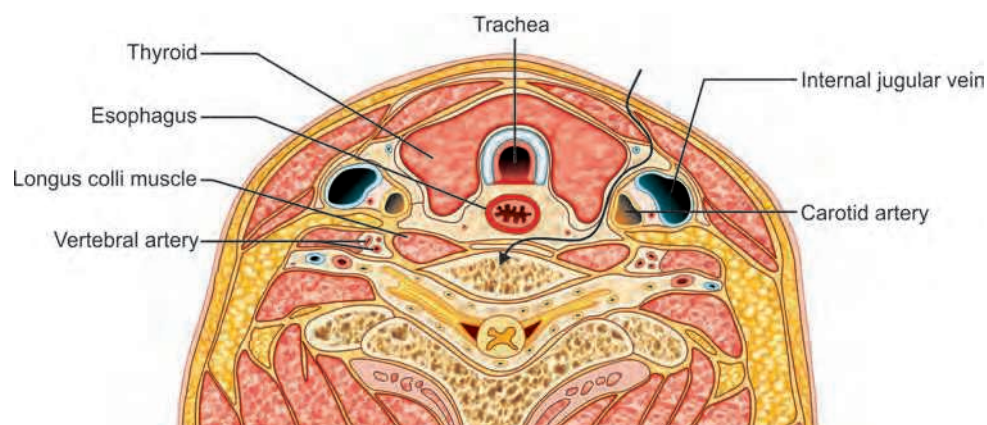


Fig. 42.2: Cross-sectional anatomy for the anterior approach to the cervical spine.

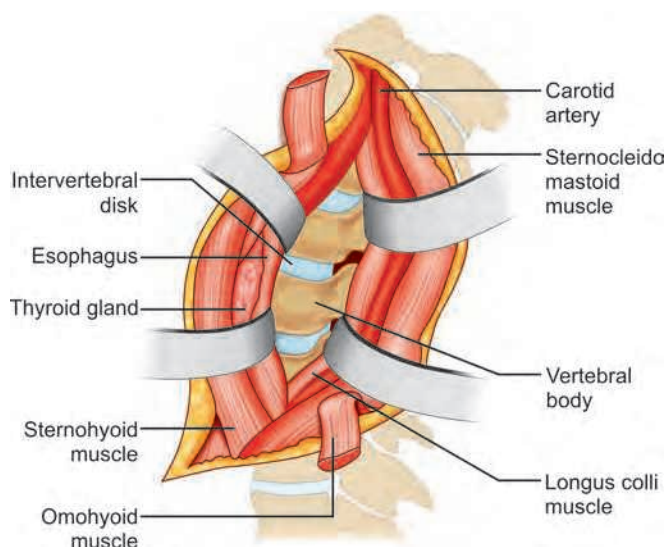


Fig. 42.3: Exposure of the anterior aspect of the cervical spine with bilateral longus colli muscle retracted.

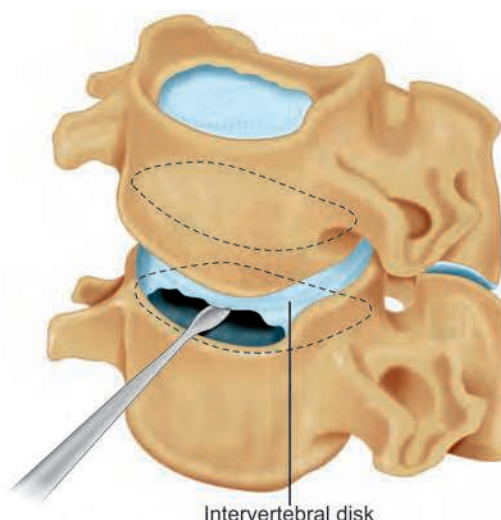
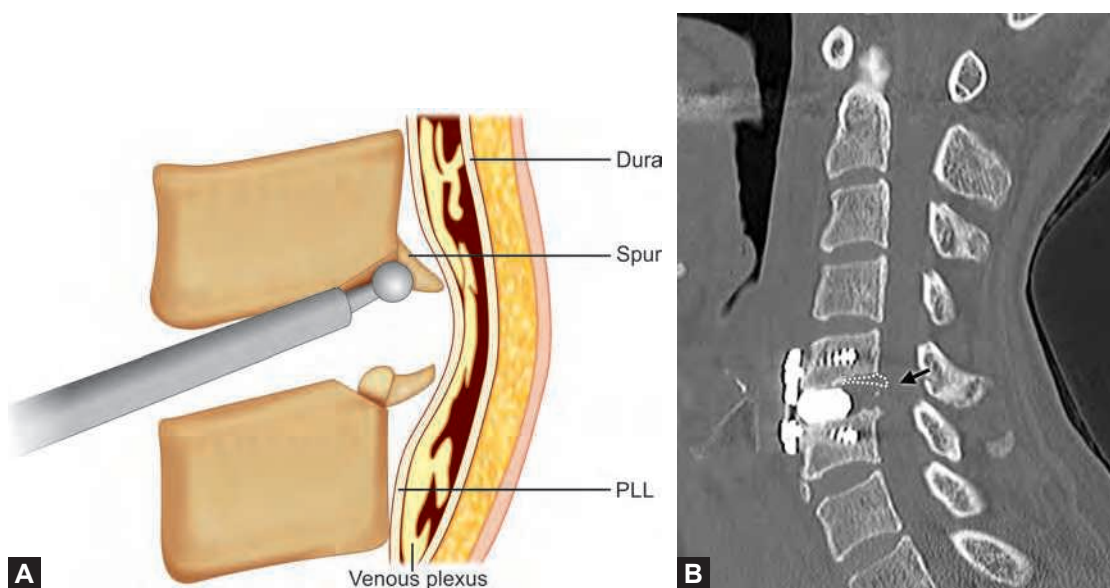


Fig. 42.4: Discectomy: the intervertebral disks are curetted as far as the bilateral uncovertebral joints. The cartilaginous endplates are removed from the superior and inferior surfaces of the disc space.

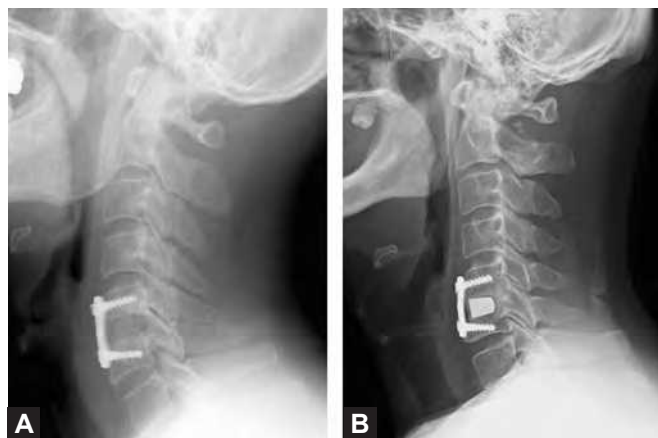
Corpectomy, Hybrid Procedure, and Circumferential Fusion

An alternate method to improve fusion rates after multilevel decompressions is a corpectomy. In addition to improving fusion rates, a corpectomy provides a more extensive decompression. Since a corpectomy removes the entire posterior cortex, it is effective for conditions with stenosis posterior to the vertebral body. Stenosis at two adjacent levels can be decompressed with a single-level corpectomy compared with a two ACDF. For a two-level ACDF, there are four bone-graft interfaces compared with only two interfaces for one-level corpectomy. The risk of

pseudarthrosis is, therefore, generally less with corpectomy than with multilevel ACDF. Hilibrand et al. retrospectively compared 131 patients undergoing multilevel ACDF to 59 patients undergoing multilevel corpectomy.¹¹ The rate of nonunion was 34% in the multilevel ACDF, whereas 7% of nonunion cases were found in the corpectomy group. However, there were six cases with graft dislodgement, and four patients undergoing corpectomy required revision surgery. A systematic review comparing ACDF and corpectomy also revealed that the nonunion rate among patients who underwent ACDF was significantly higher than that of patients who underwent corpectomy for multilevel cervical spondylosis, while blood loss and



Figs. 42.5A and B: (A) Extrication of osteophyte is performed by further trimming upward and downward from the posterior rims using a diamond burr. (B) The computed tomography image shows the extraction of osteophyte of the upper vertebrae that compressed the spinal cord preoperatively (arrow). (PLL: Posterior longitudinal ligament).



Figs. 42.6A and B: Lateral views of the X-rays following anterior cervical discectomy and fusion using iliac crest autograft (A) and hydroxyapatite spacer (B).



Fig. 42.7: Hybrid procedure of anterior cervical discectomy and fusion and corpectomy using hydroxyapatite spacer.

the rate of graft dislodgement in patients who underwent corpectomy were higher than patients who underwent ACDF.⁴⁸ In deciding between the two procedures, the risks associated with corpectomy, including more blood loss, graft dislodgement, and hardware failure, should be taken into account.⁴⁹ However, corpectomy may be considered preferable to multilevel ACDF, especially in higher-risk patients, such as recent smokers and diabetics, or in cases that require revision surgery.

Hybrid procedures of ACDF and corpectomy can also be applied for multilevel disease (Fig. 42.7). This hybrid procedure provides both sufficient decompression and maintenance of stability. Ashkenazi et al. reported the cases of multilevel disease that underwent the hybrid procedures of corpectomy and ACDF. In this study, all 13 patients achieved fusion without additional posterior instrumentation.⁵⁰ Anterior decompression with circumferential fusion is an option for cases of multilevel (three

or more) spondylosis or ossification of the PLL requiring extensive decompression and fusion. The major disadvantage of this method is greater invasion for the patients with prolonged operating time. However, the additional posterior fusion improves the fusion rate and decrease the incidence of graft-related complications.⁵¹

Graft Material

An autologous tricortical graft harvested from the iliac crest can provides excellent clinical results in achieving fusion.⁵² However, there are significant complications at the donor site with this method, including donor site pain, hematoma, infection, fracture of the ilium, sensory disturbance, and cosmetic disability.⁵³ In addition, the rate of complications is known to be higher following anterior harvest from the iliac crest compared to posterior harvest.⁵⁴ Because of the morbidity associated with autograft harvesting, alternative graft materials for ACDF have been developed.⁵⁵⁻⁵⁷ Fibula allograft is considered to be an excellent option, but the union rate is not as high as with iliac autograft.⁵² Furthermore, this allograft is not commercially available in some Asian countries, including Japan. Other options include titanium or polyetheretherketone (PEEK) cages, polymethylmethacrylate (PMMA), and an osteoconductive ceramic spacer including hydroxyapatite.^{55,58-61} Our recent experience with hydroxyapatite with percutaneously harvested iliac crest bone has been positive (Yoshii et al. 2013)⁶² (see Fig. 42.6). Bone morphogenetic proteins (BMPs) are an unrefined graft technology, and guidelines on dosage and delivery are currently being developed.⁶³ Although BMPs demonstrate impressive osteoinductive properties, they are currently hindered by significant cost constraints and complications.⁶⁴ Use of BMP in the anterior cervical spine is contraindicated secondary to its associated with postoperative swelling and significant airway complications. Other composite bone grafts present theoretical benefits; however, no consistent algorithm has been proposed. The cost of adjuvant therapies should also be taken into account.

Anterior Plating

Anterior cervical fusions were historically performed as stand-alone structural grafts and required prolonged bed rest or immobilization. Anterior cervical instrumentation was initially used in cases of cervical trauma. Indications for using plate fixation have been expanded over time to include degenerative cases. Hence, there has been a

progressive increase in the number of surgeries utilizing anterior cervical fusion and plating. Along with increased use of plating systems, plate designs have evolved over time. Orozco and Houet⁶⁵ described the use of a one-third tubular plate in the 1970s. Caspar developed a trapezoidal plate in the 1980s, and he used this plate for various indications, including trauma, tumors, and revision surgery.⁶⁶ Early devices required penetration of the posterior cortex of the vertebral body, which was associated with the risk of dural penetration. Furthermore, failure at the interface between the implant and host bone and subsequent graft dislodgement were frequently observed in multilevel fusion cases.⁶⁷ The second-generation systems featured screws fixed to the implant and permitted screw convergence on placement. The latest third-generation systems consist of dynamic semiconstrained plates that accommodate the normal settling of the graft, avoid stress shielding of the anterior column, and provide normal strut graft loads.⁶⁸

COMPLICATIONS

There are various complications related to the retraction and dissection of the vascular and nervous structures. Common complications are recurrent laryngeal nerve palsy, dysphagia, and wound hematoma. Recurrent laryngeal nerve injury occurs in 2–11% of patients, although the symptoms are often minor and resolve spontaneously.^{69,70} The mechanism includes direct injury, traction, edema, or tethering of the recurrent laryngeal nerve against the endotracheal tube.⁶⁹ Recurrent laryngeal nerve injury can be minimized using gentle tissue retraction. A left-sided anterior approach to the spine is recommended because the course of the recurrent laryngeal nerve is more constant on the left than on the right.⁷¹

Dysphagia is associated with retropharyngeal tissue edema from esophageal retraction or from plate prominence. The incidence of dysphagia is reported to be as high as 50% postoperatively, but this generally decreases over time.⁷² Postoperative dysphagia occurs more frequently in women and in cases of multilevel anterior fusion. The use of lower profile plates may decrease the risk for dysphagia.⁷³

The development of a postoperative wound hematoma is also common and is a potentially catastrophic complication. These present mainly as a neck mass associated with dysphagia, and occasionally with respiratory distress. The incidence of a postoperative hematoma is reported to be 1–11%.⁷⁴ Use of a drain is useful to decrease the risk of a postoperative hematoma.

C5 palsy is a well-recognized complication that can occur with either anterior or posterior cervical surgery. The incidence of postoperative C5 palsy following surgery for cervical compression myelopathy has been reported in an average of 4.6% (range 0–30%) of cases. The average incidences were 4.3% (range 1.6–12.1%) in cases of anterior decompression and fusion and 4.7% (range 0–30.0%) in cases of posterior decompression.⁷⁵ C5 palsy immediately following surgery is presumably due to direct injury to the nerve root.⁷⁶ The risk of neural injury is reported to be high in patients with ossification of the PLL.⁷⁷ In patients undergoing an anterior procedure, some authors have suggested that C5 palsy results from the kinking of the nerve root at the lateral part of the residual spur or ossified PLL.⁷⁵ Other authors have hypothesized that displacement of the graft makes the neural foramen narrow, thereby causing compression of the nerve root.⁷⁸ The clinical symptoms consist of deltoid weakness and radicular arm pain. Most patients can expect to experience a spontaneous recovery within 1 year.⁷⁵ It is critical to encourage passive shoulder range of motion to prevent a frozen shoulder.

Esophageal perforation during an ACDF is potentially disastrous complication.⁷⁹ The perforation can be identified intraoperatively by filling the esophagus with indigo carmine via a nasogastric tube while blocking the esophagus distal to the tube with a finger before wound closure or by performing intraoperative endoscopic esophagoscopy. After surgery, the presence of subcutaneous emphysema on X-rays or CT scan might be indicative of esophageal perforation, and the patient needs to be further examined and appropriately treated.⁷⁴ Vertebral artery injury can occur from excessive lateral dissections or from an abnormal course of the vertebral artery. The width of the corpectomy should be carefully planned before surgery using the preoperative CT images to avoid the vertebral artery. The uncovertebral joint is a reliable anatomical landmark for the lateral border of the vertebral body. In most cases, there is sufficient collateral flow to avoid severe permanent neurological deficit, but transient deficits can be seen in 50% of patients. In cases with dominant vertebral artery injury, permanent neurologic injury can occur.⁸⁰ If a vertebral artery injury is identified, pressure is applied with hemostatic agents and a cottonoid patty for several minutes. During this time, it is useful to call an assistant into the room as well as inform interventional radiology of the injury. Most often, the injury is a partial injury and has the potential to stop through vasoconstriction. If it does not stop, the vertebral artery can be ligated or repaired. The

artery is exposed by following the uncinat process out laterally over the transverse process; the bone overlying the artery is then resected with a small Kerrison. An angiogram is performed postoperatively to ensure that there is not a vertebral artery dissection that needs to be embolized.

KEY POINTS

- Most patients with CSM have a stepwise progression in their neurological dysfunction after the onset of symptoms. Surgery can alter the natural history and change the prognosis of patients with CSM.
- The choice of either an anterior or a posterior procedure for decompression of CSM is based on multiple factors, such as the location of the compressive pathology, the extent of the degenerative process, and the sagittal alignment of the cervical spine.
- An alternate method to improve the fusion rate after multilevel decompression is corpectomy. Corpectomy provides a more extensive decompression. Hybrid procedures of ACDF and corpectomy can also be applied for multilevel disease.
- Various graft materials were reported for use in the anterior procedure, such as autograft, allograft, titanium cage, PEEK cage, PMMA, and hydroxyapatite.
- Complications related to the anterior surgical procedure include recurrent laryngeal nerve injury, dysphasia, C5 palsy, hematoma, esophageal perforation, and vertebral artery injury.

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■ KEY REFERENCES

Smith GW, Robinson RA. The treatment of certain cervical-spine disorders by anterior removal of the intervertebral

Posteriorly Based Surgical Treatment of Cervical Spondylotic Myelopathy

Brian W Su, Nestor Fiore

Snapshot

- » Indications
- » Outcomes

- » Complications

INTRODUCTION

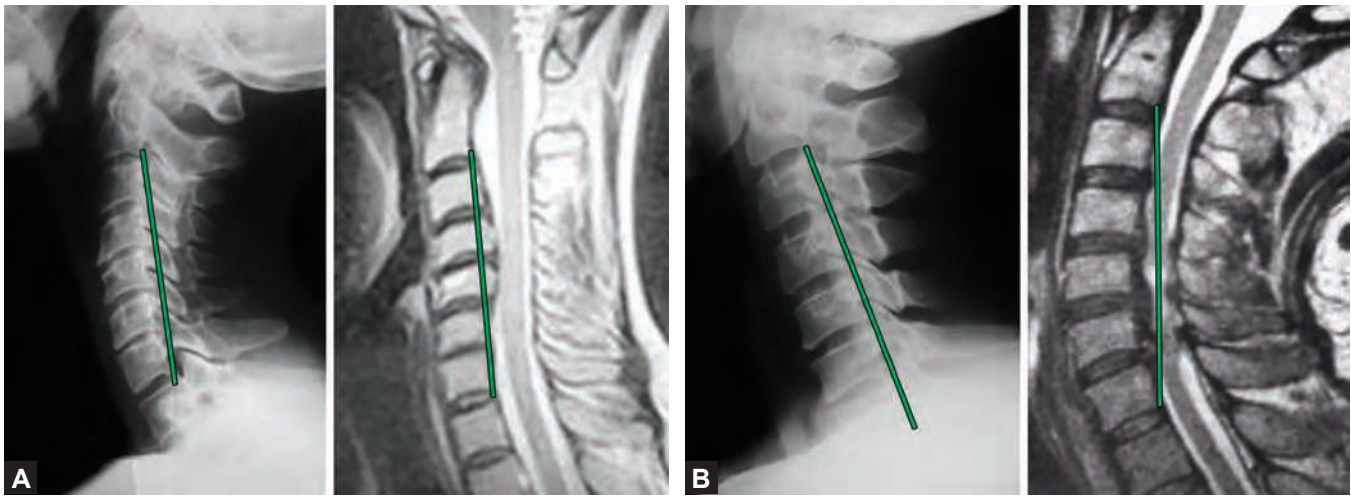
The causes of cervical spondylotic myelopathy (CSM) include compression at single or multiple levels, cervical malalignment, instability, or congenital stenosis. The decision of using an anterior or posterior surgical approach is often controversial and is based on the number of segments involved, location of compression (anterior vs. posterior), and radiographic sagittal alignment.

Any posteriorly based procedure relies on the ability of the spinal cord to float away from the spine after it is decompressed. In the presence of a kyphotic spine, despite taking pressure off posteriorly, the cord can potentially remain draped over the anterior disk osteophyte complexes leading to inadequate decompression of the cord. A posteriorly based procedure is ideally performed in patients with adequate lordosis. It is critical to assess cervical lordosis, cervical sagittal balance, as well as the location of the compressive elements through the posterior spinal line (PSL) when choosing a posterior based procedure.^{1,2} Cervical alignment has traditionally been measured with a C2-C7 Cobb's angle. It is our preference to use the method described by Toyama et al. that involves drawing a line from the posterior inferior corner of C2-C7 and examining its relationship to the posterior vertebral bodies. If the line is posterior to the posterior vertebral bodies, then the overall alignment of the spine is lordotic.^{3,4} If the line is at the same level as the posterior bodies, then the cervical spine is neutral. If the line is anterior to the



Fig. 43.1: Assessing cervical lordosis as defined by Toyama by drawing a line from the posterior corner of C2 to the posterior superior corner of C7. The alignment is neutral to slightly lordotic as the line is just posterior to the posterior vertebral bodies. Cobb angle in red.

vertebral bodies, then the alignment is kyphotic (Fig. 43.1). Although a magnetic resonance imaging (MRI) is useful for determining the location and severity of spinal cord compression, it should not be used to assess cervical alignment. Occasionally, a lateral radiograph can demonstrate well-maintained lordosis, while the sagittal MRI shows a neutral or kyphotic spine. Conversely, a lateral radiograph may show lack of normal lordosis, while the supine MRI shows that the patient has the ability to achieve lordosis (Figs. 43.2A and B). These differences are most likely



Figs. 43.2A and B: (A) Lateral radiograph demonstrating lordosis with a sagittal MRI of the same patient demonstrating kyphosis. (B) Lateral radiograph demonstrating loss of lordosis and straightening of the cervical spine with a sagittal MRI of the same patient demonstrating lordosis.

attributable to the fact that the patient is supine during the MRI. It is our preference to measure cervical alignment on a standing upright lateral radiograph when determining if a patient has enough lordosis to undergo a posterior procedure. A lateral extension radiograph is also critical as the patient's ability to achieve lordosis on extension gives the surgeon further information on the ability to achieve appropriate alignment during surgery in the setting of a fusion. In patients who have too much pain to actively extend, a cross table lateral radiograph with the patient passively extended can be useful when a bump is placed under the periscapular region.

Cervical lordosis is related to both overall and cervical sagittal balance. Overall sagittal balance dictates that a vertical line drawn from the C7 body on a 36 inch full length lateral radiograph should coincide with the posterior superior corner of the L5-S1 disk space.⁵⁻⁸ Both increased thoracic kyphosis and decreased lumbar lordosis in aging patients leads to compensatory lordosis of the cervical spine in order for the patient to maintain horizontal gaze.^{9,10} Once overall positive sagittal balance is corrected by operating on the lumbar spine, there is improvement of the abnormal cervical hyperlordosis through reciprocal changes.¹¹ Cervical lordosis should be evaluated with the knowledge that it is affected by overall sagittal balance. Cervical sagittal balance is measured by the C2-C7 cervical sagittal vertical axis (C2-C7 SVA), which is the distance from the C2 plumb line to the posterior superior corner of the C7 vertebral body.¹² The outcome of posteriorly based cervical spine surgery has been shown



Fig. 43.3: Cervical sagittal balance measured by the C2-C7 SVA in red (distance of the C2 plumb line in green to the posterior superior corner of C7).

to be related to preoperative cervical sagittal balance.¹² A C2-C7 SVA value of >40 mm correlates with increasing severity of disability following surgical reconstruction (Fig. 43.3).¹²

In addition to assessing radiographic alignment, it is also important to assess the location of the compressive elements and its relationship to the alignment of the spinal cord itself within the canal. In the experience of the senior author, a posterior approach can be performed regardless of radiographic alignment as long as the PSL¹³ is positive, recognizing that the ultimate goal is to

realign the spinal cord in the spinal canal. The PSL is a line drawn from the origin of the posterior laminar attachment in the middle sagittal MRI at the levels where the cord is centered in the canal (Fig. 43.4).¹³ A positive PSL indicates that there are osteoligamentous compressive structures anterior to the PSL. The PSL is independent of cervical alignment and is used to determine the

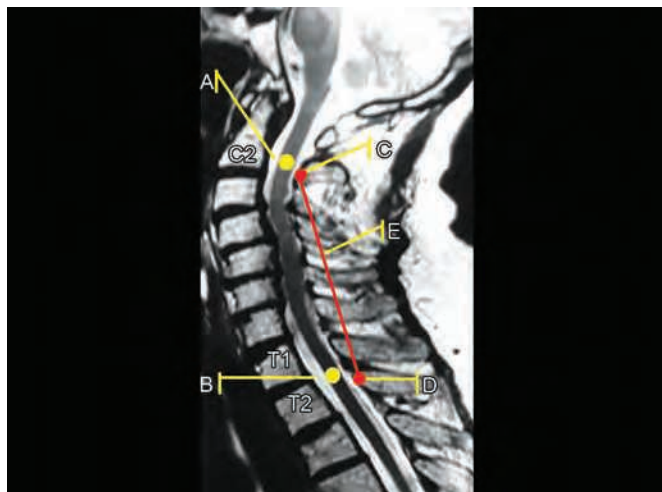
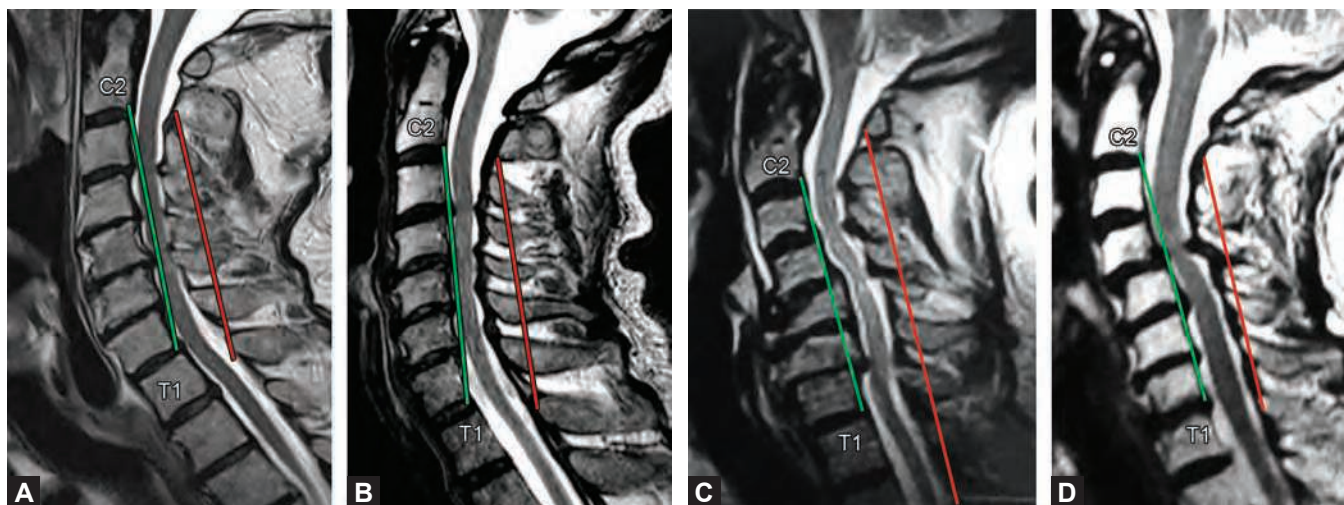


Fig. 43.4: Posterior spinal line (PSL). Point A is the cranial level where the spinal cord is centered in the canal. Point B is the caudal level where the spinal cord is centered in the canal. Point C is the laminar attachment point at the cranial level where the cord is centered in the canal. Point D is the laminar attachment point at where the caudal cord is centered in the canal. The posterior spinal line is a line connecting Points C and D. A positive PSL indicates that compressive structures are anterior and a posterior approach alone can realign the cord within the canal.

ability of the cord to center itself in the canal (Figs. 43.5A to D). A positive PSL dictates that a posterior approach would allow for posterior cord float, placing the cord parallel to the PSL and aligning it inside the spinal canal. A negative PSL indicates that there are no anterior osteoligamentous structures in front of the PSL, suggesting that an anterior approach may be necessary (Figs. 43.6A and B). Similarly, Fujiyoshi et al. described the K line as a line that connects the midpoints of the spinal canal at C2 and C7 in patients with ossification of the posterior longitudinal ligament (OPLL).¹⁴ They found that posterior shift of the spinal cord and neurologic improvement was not obtained after posterior decompression surgery in the K line negative group.¹⁴ Using the PSL to guide surgical approach emphasizes the importance of centering the spinal cord within the canal rather than correcting absolute radiographic spinal alignment. This approach is a novel one that allows for the potential of performing a posterior approach even in the setting of a slightly kyphotic spine (Figs. 43.7A and B).

Any patient undergoing a posterior procedure should also obtain a computerized tomography (CT) scan to evaluate bony anatomy. Ossification of the posterior longitudinal ligament can be detected on CT and typically pushes the surgeon toward a posteriorly based procedure secondary to the high incidence of incidental durotomy with an anterior procedure. The CT scan can also help visualize the cervical pedicles as well as the lateral masses to aid in placement of hardware posteriorly.



Figs. 43.5A to D: Representation of cases with positive PSL independent of spinal sagittal alignment. (A) Spine in lordosis with positive PSL. (B) Spine straight with positive PSL. (C) Spine in kyphosis with positive PSL. (D) Spine in S with positive PSL.

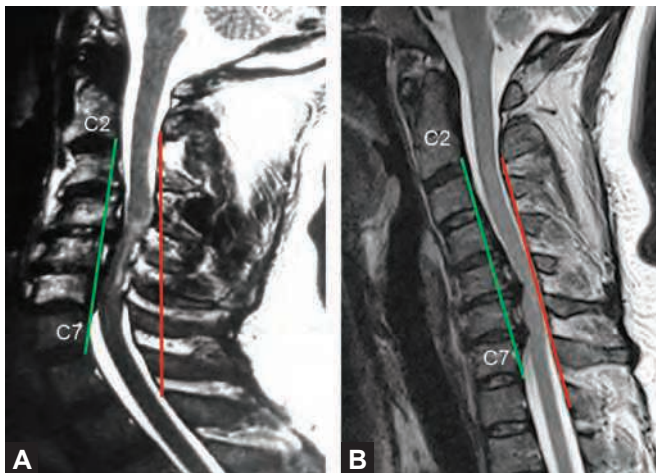
INDICATIONS

Most surgeons elect to use anterior or anterior/posteriorly procedures when the pathology is at three or less levels and the compression is secondary to focal disease at the anterior disk osteophyte complexes.¹⁵ Ideal patients for posterior only procedures include those who have diffuse narrowing behind the disks and vertebral bodies

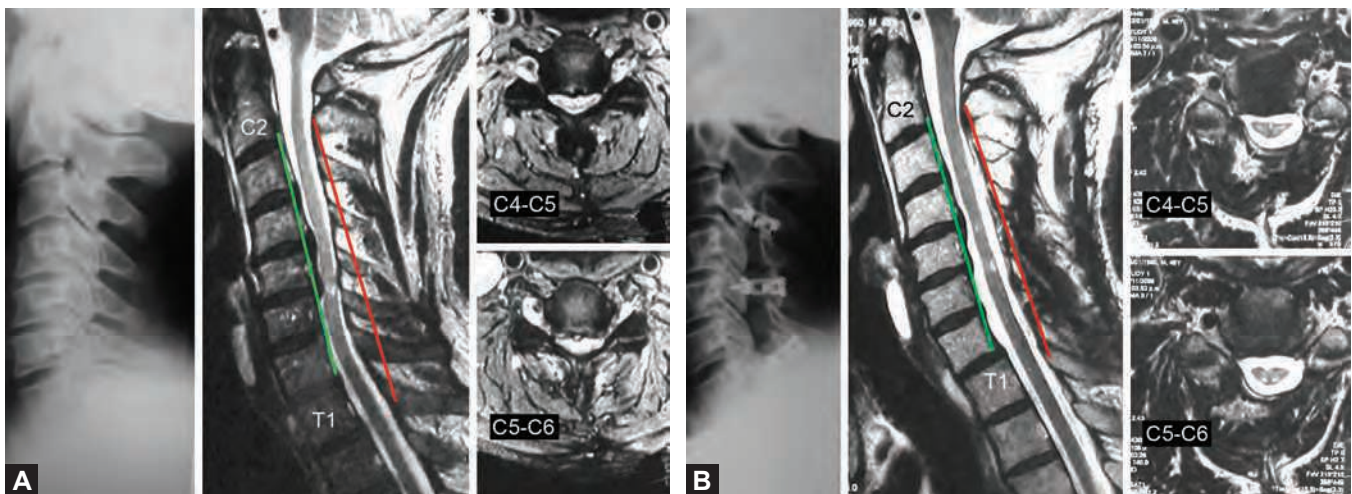
secondary to OPLL, congenital stenosis, or more than three levels of compression. Although unusual, isolated posterior compression of the spinal cord from buckling of the ligamentum flavum or a cervical facet cyst is also a good indication for a posterior decompression. Posteriorly based techniques include laminoplasty, laminectomy alone, or laminectomy/laminoplasty and fusion. In the setting of focal anterior compression that exists simultaneously with congenital or multilevel stenosis, an anterior decompression and fusion procedure can be combined with a multilevel posterior procedure.

Laminectomy Alone

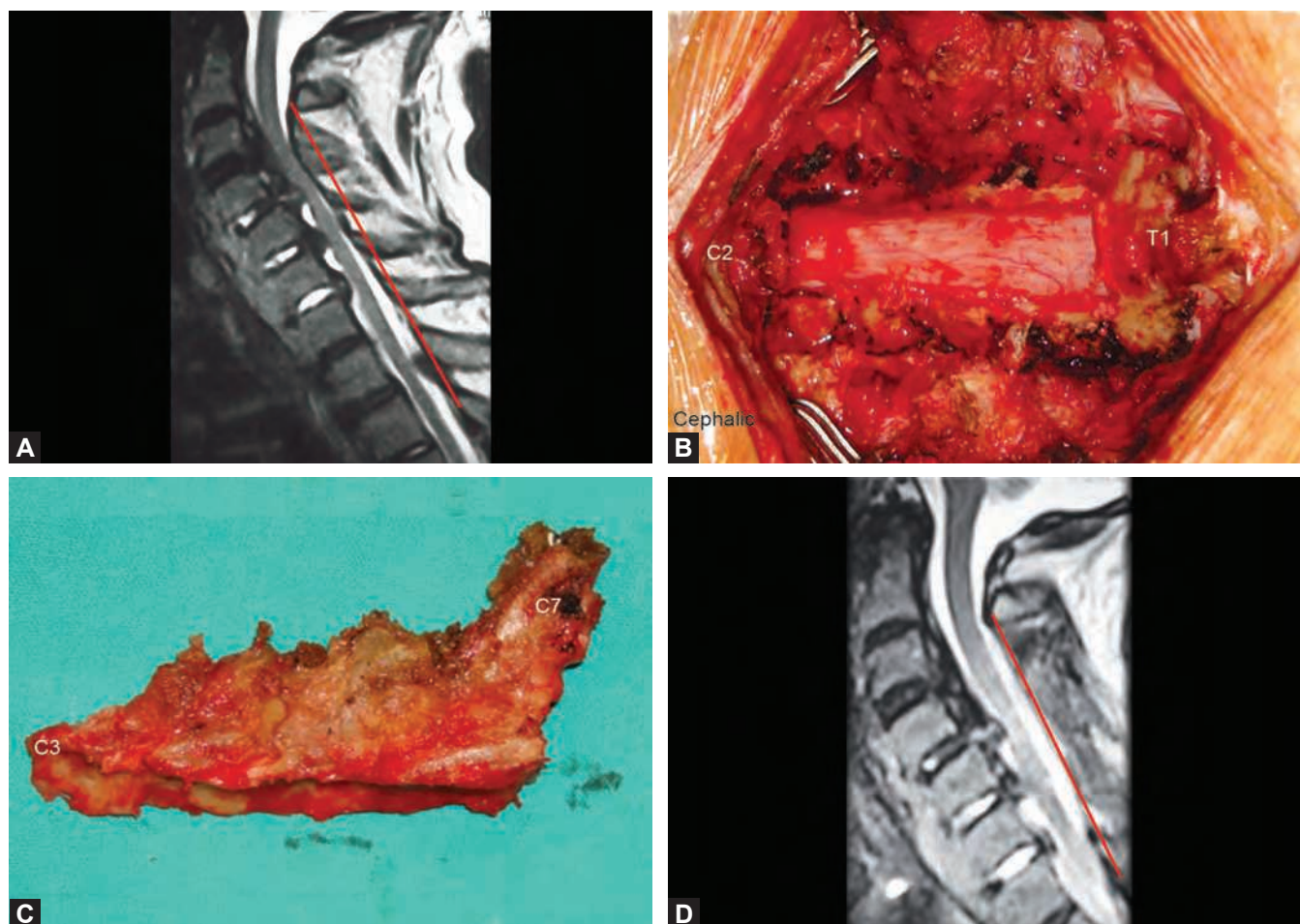
Removal of the entire lamina without reconstruction of the posterior elements is an option for treatment of CSM. Miyazaki reported the results of 155 patients who underwent laminectomy and found that 82% showed improvement based on Japanese Orthopaedic Association (JOA) scores at 1-year follow-up.¹⁶ However, longer follow-up of patients following laminectomy alone demonstrated that late neurological deterioration occurred in 23% of patients.¹⁷ A systematic literature review determined that laminectomy alone can be effective in treating CSM with limitations being increased risk of postoperative kyphosis compared to anterior techniques, laminoplasty, or laminectomy with fusion.¹⁸ Several authors have also reported kyphosis following laminectomy with Herkowitz et al.¹⁹ and Kaptain et al.²⁰ reporting a 25% and 21% incidence, respectively, at 2-year follow-up. Postlaminectomy kyphosis



Figs. 43.6A and B: Both cervical spines have kyphotic alignment based on the measurement by Toyama (green line). (A) Positive posterior spinal line (PSL) demonstrating compressive elements anterior to the PSL indicating that a posterior approach may be used. (B) Negative PSL demonstrating that there are no compressive elements anterior to the PSL indicating that a posterior approach is not recommended.



Figs. 43.7A and B: (A) Representative patient with myelopathy in the setting of a kyphotic spine (green line) and positive posterior spinal line (PSL) (red line) Preoperative sagittal and axial view. (B) Postoperative sagittal and axial view demonstrating adequate posterior cord float despite the presence of kyphosis.



Figs. 43.8A to D: (A) Magnetic resonance imaging (MRI) showing ankylosis, severe stenosis, and neutral alignment. (B) C3-C7 laminectomy without a fusion. (C) The posterior elements are removed in a monoblock manner. (D) Postoperative MRI demonstrating a widened canal and maintenance of sagittal alignment.

and instability is the most common complication following an isolated laminectomy and is one of the primary drivers for its decreased use for treatment of CSM. Interestingly, deformities of the cervical spine occurring after surgery do not always appear to cause symptoms or neurologic abnormalities.^{18,21}

Guigui et al. examined 58 patients for spinal deformity and instability after multilevel cervical laminectomy for CSM and found that at an average of 3.6-year follow-up, 31% of patients had postoperative changes in spinal alignment and 25% had destabilization at one or more levels.²¹ All of the levels destabilized on the postoperative films had instability on the preoperative dynamic radiographs.²¹ Kaptain et al. also found that kyphosis was twice as likely to occur following an isolated laminectomy if preoperative imaging studies demonstrated a straight spine.²⁰

It is our recommendation that a laminectomy procedure should be avoided when there is loss of normal cervical lordosis on the preoperative neutral lateral radiograph and if there is instability of flexion extension radiographs preoperatively. If a laminectomy requires the addition of a laminoforaminotomy with removal of >50% of the facet to decompress the cervical roots for concomitant radiculopathy, a fusion should be performed. The ideal patient for a cervical laminectomy is an elderly patient with no instability/kyphosis who has a severely degenerative spine with little risk of postoperative instability (Figs. 43.8A to D). The technique for a cervical laminectomy is covered in the laminectomy and fusion section of this chapter.

Postlaminectomy kyphosis can present as increasing neck pain, loss of horizontal gaze secondary to kyphosis, and worsening myelopathy/radiculopathy. Symptomatic



Figs. 43.9A and B: (A) 48-year-old female who underwent a laminectomy alone for myelopathy. She presented four years later with recurrent symptoms, instability, and loss of normal lordosis. (B) She subsequently underwent a four level ACDF to correct the instability and kyphosis.

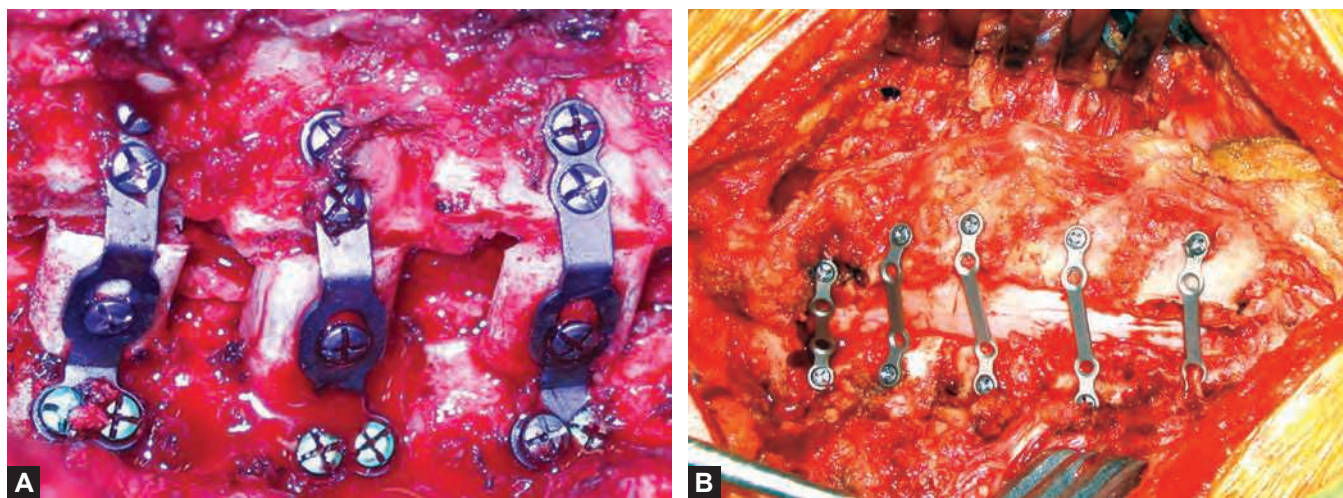
postlaminectomy kyphosis should be treated with a deformity correcting fusion procedure to prevent worsening of the deformity.^{22,23} A CT and MRI should be performed to assess the amount of bone stock available for fixation as well as the degree of stenosis. The treatment of postlaminectomy kyphosis is dependent of whether the patient has a fixed or flexible deformity, and the degree of sagittal imbalance. A standing 36 inch lateral radiograph to assess spinal sagittal balance should also be obtained when planning fusion levels. Flexion/extension radiographs should also be obtained to assess the flexibility of the deformity. Flexible deformities can be treated with a revision posterior cervical fusion with lateral mass or pedicle fixation to fuse the patient in lordosis. Some authors have reported a 96% fusion rate following treatment of postlaminectomy kyphosis with wiring of the posterior facets.²² There are few clinical studies on the treatment of postlaminectomy kyphosis with modern lateral mass or pedicle fixation. This is likely secondary to the phasing out of treatment of CSM with a laminectomy alone as the awareness of postlaminectomy kyphosis or instability increases. It is our recommendation that kyphosis treated with posterior fixation alone should be carried out to the proximal thoracic spine to avoid distal junctional kyphosis.

Fixed deformities can be released with multilevel unciniate to unciniate anterior cervical discectomies and fusion (ACDF) followed by anterior structural grafting to build in cervical lordosis. This can be followed by anterior plate fixation to fuse the patient in lordosis if three or fewer levels

have been grafted or anterior and posterior fixation if more than three levels were involved. In our experience even in the setting of a fixed deformity, multilevel ACDFs can be very useful to restore lordosis and simultaneously decompress the spinal cord from disk osteophyte complexes. Occasionally, a cervicothoracic osteotomy or a posterior-anterior-posterior release can be used for severe deformities. It is our preference to restore lordosis with multiple ACDFs rather than perform posterior osteotomy, as the correction of the lordosis is more anatomical and less segmentally acute with an ACDF (Figs. 43.9A and B).

Laminoplasty

The laminoplasty procedure is a nonfusion procedure aimed at expanding the spinal canal while preserving its bony architecture. Although the Japanese popularized this technique for the treatment of OPLL,^{24,25} indications for a laminoplasty have been expanded to treating stenosis secondary to CSM or congenital stenosis. Several authors have reported a neurological recovery rate following an open-door laminoplasty to be approximately 60% with patients <60 years and with <1 year of symptoms having better results.^{26,27} Yoon et al. performed a systematic review of studies explicitly designed to evaluate the effect of preoperative factors on patient outcome after cervical laminoplasty for CSM or OPLL.²⁸ They found that hill-shaped lesions may be associated with poorer outcomes as well as patients with increased severity of disease and a longer duration of symptoms.²⁸ The senior author N.F.



Figs. 43.10A and B: Laminoplasty with (A) and without (B) the use of structural bone graft and the use of mini plates.

reported on the outcomes of 78 patients who underwent an open-door laminoplasty. Sixty-nine patients presented some improvement according to the Nurick's scale (90%), and there have been no changes in stability or postoperative alignment.¹³

Since laminoplasty is not a fusion procedure, preoperative alignment of the spine is ideally nonkyphotic so that the decompressed spinal cord can float posteriorly away from the anterior elements. Several authors have reported that a laminoplasty in a kyphotic spine leads to poorer clinical outcomes.^{29,30} Even in the setting of normal alignment, Aita et al. also found that laminoplasty can be associated with progressive kyphosis at 5-year follow-up.³¹

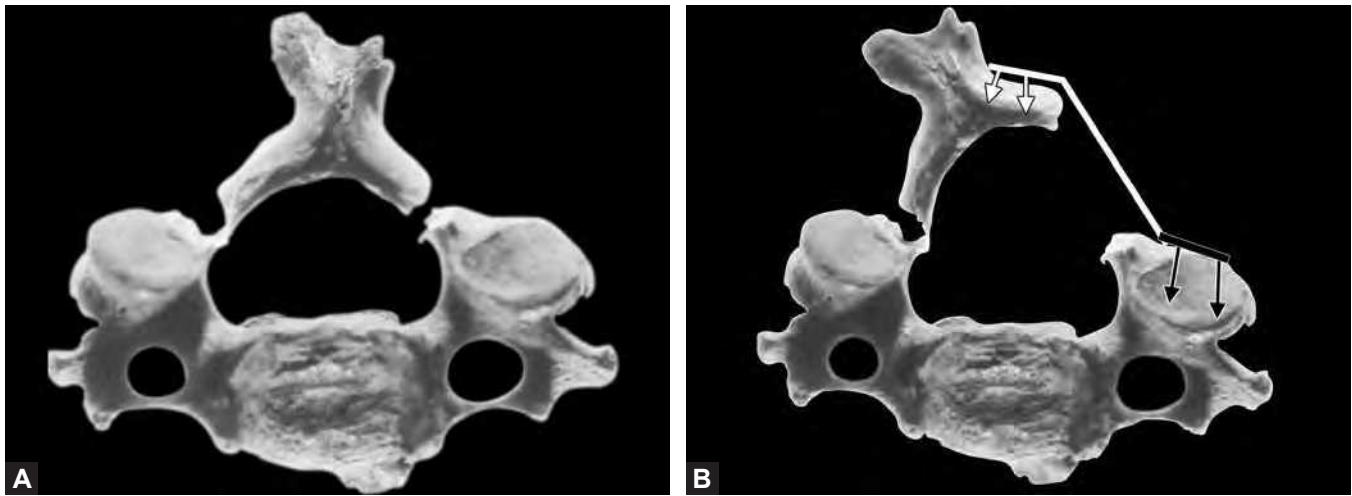
It is our recommendation that a laminoplasty procedure should only be performed in patients who do not have preoperative instability or at least neutral alignment of the cervical spine. This alignment should be assessed on a preoperative neutral lateral radiograph. The ideal candidate for a laminoplasty is a patient who has a neutral to lordotic spine with preserved range of motion (ROM) and multilevel stenosis.

We typically do not recommend a short segment laminoplasty (less than four levels) as retained lamina in the cranial or cephalad segments adjacent to the laminoplasty can tether the spinal cord as it drifts posteriorly. The majority of cases are a C3-C6, or C3-C7 laminoplasty. If there is compression at the inferior arch of C2 or superior arch of C7, a dome laminectomy can be performed adjacent to the laminoplasty. Although there are multiple techniques to performing a laminoplasty, it is our preference to perform an open-door laminoplasty with recon-

struction of the lamina with miniplates. Use of a structural graft is not always necessary and some surgeons use a miniplate without a structural graft to maintain the space open as the hinge side typically heals. Use of plates has been shown to maintain the opening and decrease loss of mobility and postoperative pain (Figs. 43.10A and B). This approach preserves most of the ligamentous structures that are important for maintaining stability.

Patients are positioned in the prone position with Mayfield tongs on chest rolls. Neurological monitoring using motor evoked potential and somatosensory evoked potentials is performed throughout the entire surgery. The head is positioned in a slightly flexed position to unshingle the lamina to ease drilling the laminoplasty trough. A midline incision is made; the fascia is identified. The avascular midline is exposed down to the spinous process using a cerebellar retractor to serially spread the paraspinal muscles, taking care of all ligamentous structures. Subperiosteal dissection of the lamina is performed at all levels to be released. It is critical to preserve all of the midline ligaments as well as the facet joint capsules. Exposure on the hinge side does not have to be more lateral than the lamina-facet junction. Exposure on the opening side needs to be more lateral requiring exposure of the lateral masses for miniplate fixation. On the opening side, a Cobb elevator can be used to gently expose the facet joint capsules; exposure of the lateral masses should be taken to the lateral aspect of the lateral mass taking care to preserve the joint capsules.

The decision of which side to open is arbitrary and is based on surgeon preference; it is our preference to

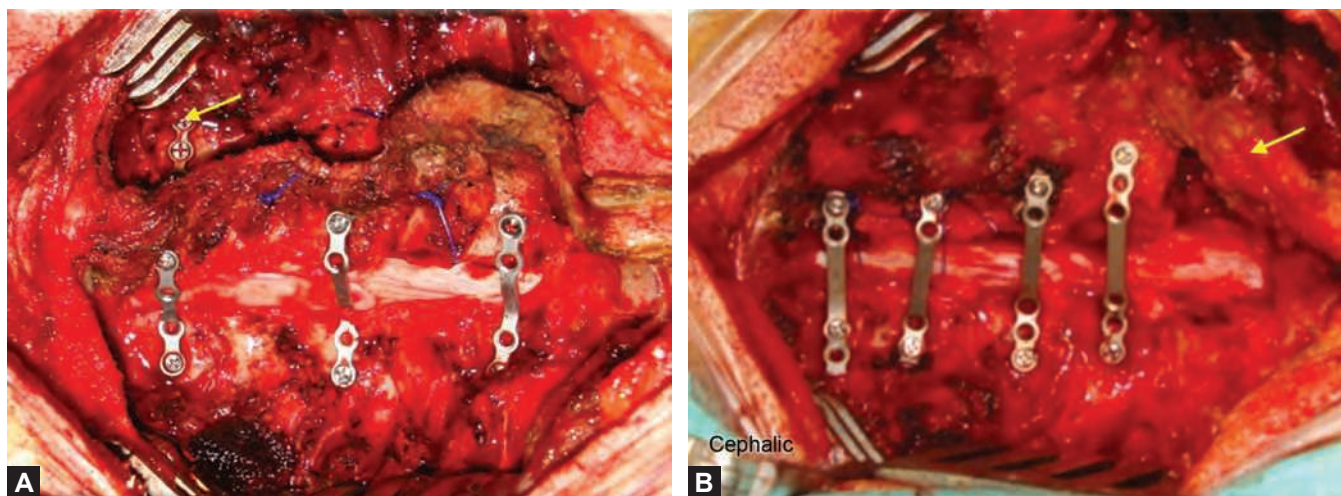


Figs. 43.11A and B: (A) Resection of outer cortex and thinning the inner cortex on one side with resection of the entire lamina on the contralateral side. The width of the laminoplasty is from one lamina facet junction to the other (22–24 mm) and wider than the width of a laminectomy (18 mm) for a laminectomy and fusion procedure. (B) Opening the osteotomy with a greenstick fracture of the contralateral side.

open the side that requires foraminotomies if there is concomitant radiculopathy. We measure the width of the lamina resection on preoperative imaging studies from one lamina–facet junction to the other. It should be noted that the width of a laminoplasty (22–24 mm) is greater than the width of a laminectomy (18 mm). A laminoplasty resection should be from one lamina–facet junction to the other, while a laminectomy should be limited to the width of the spinal cord to limit excessive cord float. This width is then set on calipers and a marking pen is used to draw lines on the lamina to help guide the laminoplasty trough. If a foraminotomy or a C2 dome laminectomy is needed, it is our preference to do all preliminary drilling with an AM-8 burr prior to the laminoplasty. This minimizes burr use while the spinal cord is exposed. An AM-8 3 mm acorn tip burr is then used to create the trough on the opening side at the lamina–facet junction. Since a 3 mm burr is used, the trough width is at minimum 3 mm. Once the lamina is removed, a 1 mm Kerrison is used to cut through the ligamentum flavum. A small 6-0 angled curette or micronerve hook can then be used above the spinal cord to make sure that the spinal cord is completely released from the underlying ligaments and lamina. Any epidural bleeding can be controlled with liquid gelfoam and bipolar electrocautery. The hinge side can then be created in a similar manner using an AM-8 burr. The outer cortex and inner cancellous bone should be drilled just up until the inner cortex. The inner cortex should be slowly thinned;

caution should be taken to not drill through the thin inner cortex. The trough width on the hinge side is typically 1 mm wider to allow for visualization of the inner cortex. While the surgeon is drilling the hinge side, his/her assistant is pushing the lamina from the opening side toward the closing side to test whether enough bone has been resected. Resection of the inner lamina should stop once there is enough give and the inner cortex starts to greenstick fracture. Patience should be taken during this step as the inner cortex has significant viscoelasticity and slow constant pressure on the spinous process toward the hinge side can open the canal significantly as time passes (Figs. 43.11A and B). If a complete osteotomy is unintentionally made on the hinge side, the underlying ligament is typically enough to allow the osteotomy to heal. However, if the hinge feels loose and is at risk of pushing on the spinal cord, a miniplate can be used to bridge the osteotomy as it heals (Figs. 43.12A and B). For a C3–C7 laminoplasty, access to the C2–C3 interspace is often difficult and requires undercutting the inferior aspect of the C2 lamina. Occasionally, if C2 is going to be included in the laminoplasty construct the inferior arch of C1 may need to be thinned. In this situation, the vertebral arteries should be protected by placing an instrument on the inferior arch of C1.

As the canal is expanded, dural adhesions may need to be released from the underlying dura with the use of a large ball tip probe or a Woodsen elevator. The cranial

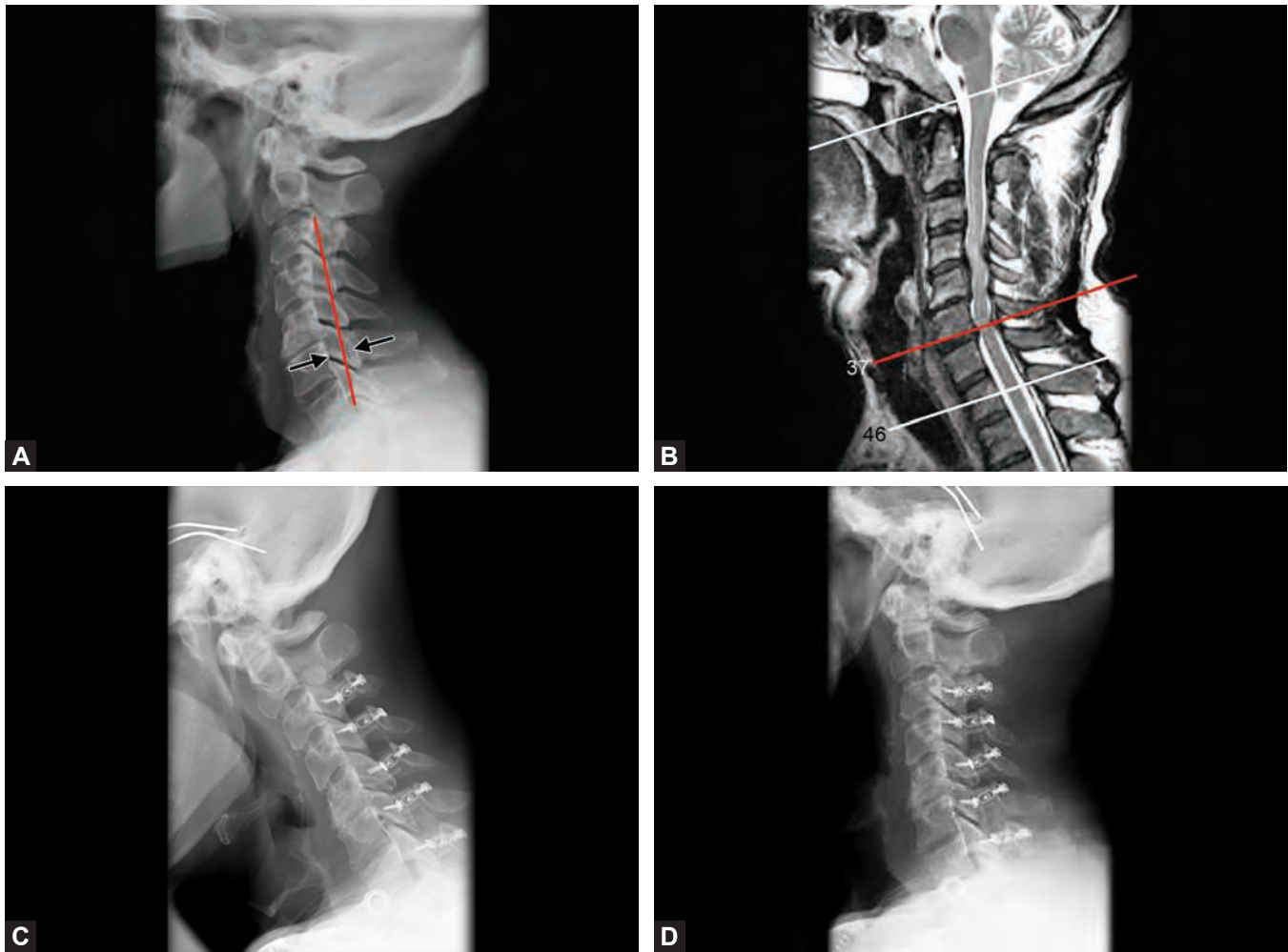


Figs. 43.12A and B: (A) Involuntary osteotomy in the lamina of the right side of C2 repaired with a miniplate (arrow). (B) Involuntary osteotomy in the lamina of the right side of C7 with resection of the posterior arch preserving the ligaments (arrow).

and caudal end of the laminoplasty is often tethered by the adjacent soft tissues. For a C3-C7 laminoplasty, resection of the flavum between C2-C3 and C7-T1 may be needed to expand the proximal and distal ends of the laminoplasty to allow C3 and C7 to open adequately. Although some surgeons elect to use miniplates alone to hold the lamina open, it is our preference to use structural allograft with miniplates. Using polyetheretherketone (PEEK) or metallic spacers rather than structural allograft is also a possibility. Most laminoplasty systems have sizers to help determine the size of the structural allograft. The opening at the distal and proximal lamina is typically 6–8 mm secondary to soft tissue tethering, while the remaining laminar segments can be opened to 8–10 mm. It is typically useful to place grafts working from caudal to cranial or vice versa as each subsequent graft creates room for the next graft in line. It is our preference to use grafts that are already attached to the miniplates, as they are placed in the defect. Once the grafts are in place, miniplates are attached to the lamina and lateral mass with small screws (Figs. 43.13A to D). It is our preference to drill with a TPS drill with a 6 mm stop prior to placement of the screws. Screws in the lamina are typically 6 mm, while those in the lateral mass are 8–10 mm. Screws in the lateral mass can be placed perpendicular to the plate or aimed slightly cranially in the style of a lateral mass screw to avoid violating the facet. Postoperatively, patients can be placed in a soft cervical collar for 2–6 weeks. Extended collar wear is not needed because the laminoplasty is not a fusion procedure.

A laminoplasty can be combined with an ACDF when there is congenital stenosis or multilevel compression in the presence of a hill-shaped lesion or a large anterior disk at one or two levels. In this situation, some surgeons begin with a multilevel laminoplasty to create room for the spinal cord. This is followed by a one or two level ACDF to safely remove the compressive anterior lesion. This approach is also useful if there is segmental kyphosis as the ACDF can be used to create lordosis. Combining a short segment ACDF with a laminoplasty avoids the need to fuse every stenotic level (Figs. 43.14A to F). It should be noted that the senior author has anecdotally noticed the resolution of anterior soft disk herniations following a posterior only decompression at 6 months postoperatively. This is most likely secondary to the pulsating effect of the CSF on the disk after the canal is decompressed and is an option when there is anterior compression from a disk herniation in the setting of multilevel cervical stenosis (Figs. 43.15A to C).

Axial neck symptoms following laminoplasty has been reported by several authors.^{32,33} Hosono et al. reported on the results of 72 patients treated for CSM with laminoplasty at an average follow-up of 40 months.³² Of all patients, 60% had postoperative axial symptoms, and in 25% of patients, the chief complaints after surgery were related to axial symptoms for >3 months.³² Some authors have proposed that preservation of the C7 spinous process³⁴ or the semi-spinalis cervicis insertion onto C2³⁵ can reduce postoperative neck pain. We believe that respecting as many ligaments as possible is critical to reducing neck pain.



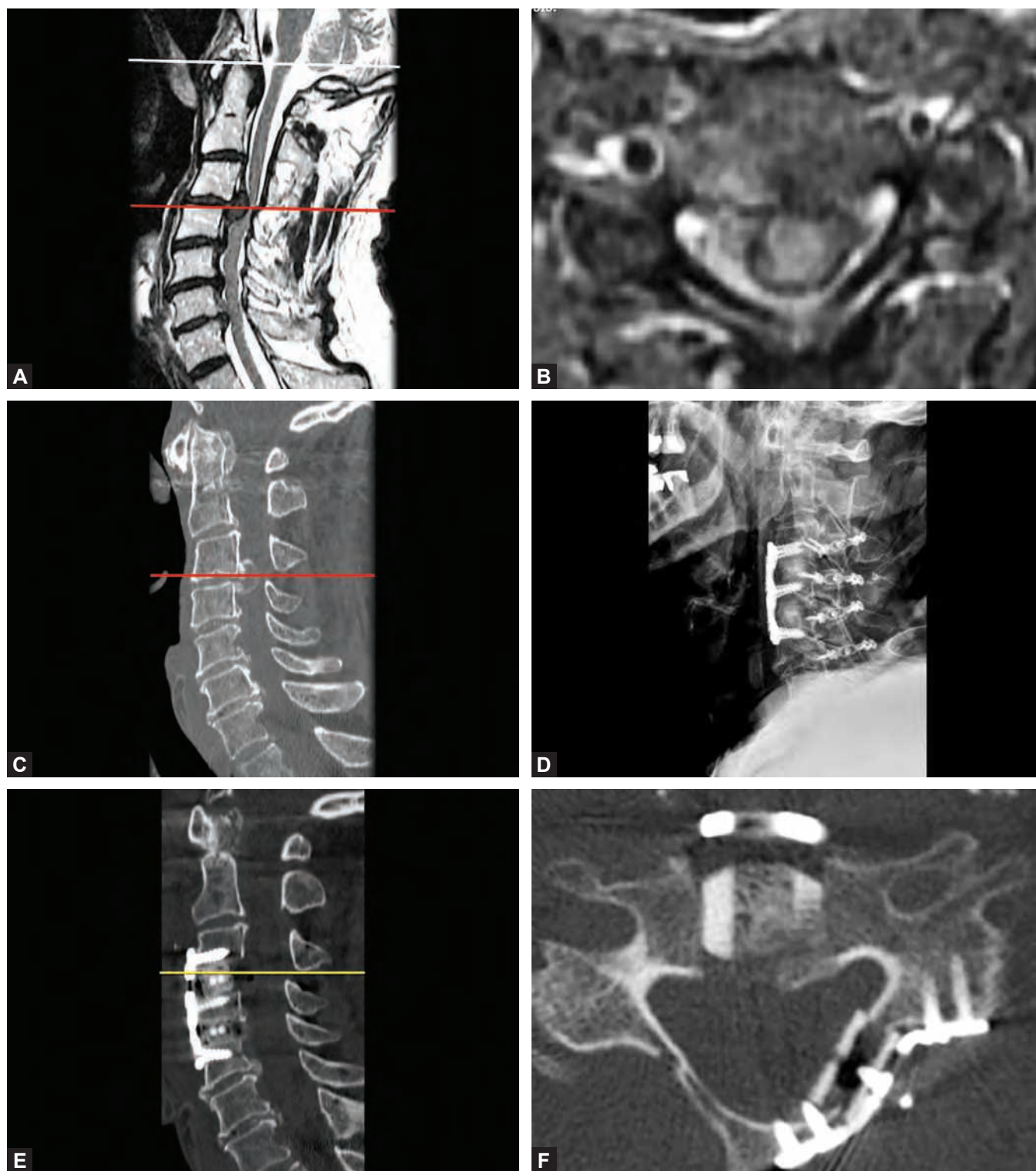
Figs. 43.13A to D: A 57-year-old male with weakness in arms/legs, balance problems and difficulty with fine motor skills. (A) Neutral X-ray with adequate lordosis. (B) Magnetic resonance imaging (MRI) showing multilevel stenosis. The patient underwent a C3-C7 laminoplasty. 1 year postoperative with maintenance of range of motion from flexion (C) to extension (D).

Some surgeons prefer to perform a laminoplasty to decompress the canal and perform a simultaneous fusion. This can be performed with custom lateral mass screws that thread through the laminoplasty plates. The screws can then be connected using a rod. Theoretical advantages of this technique include the ability to preserve midline anatomy as well as potentially limit posterior cord drift when compared to a complete laminectomy.

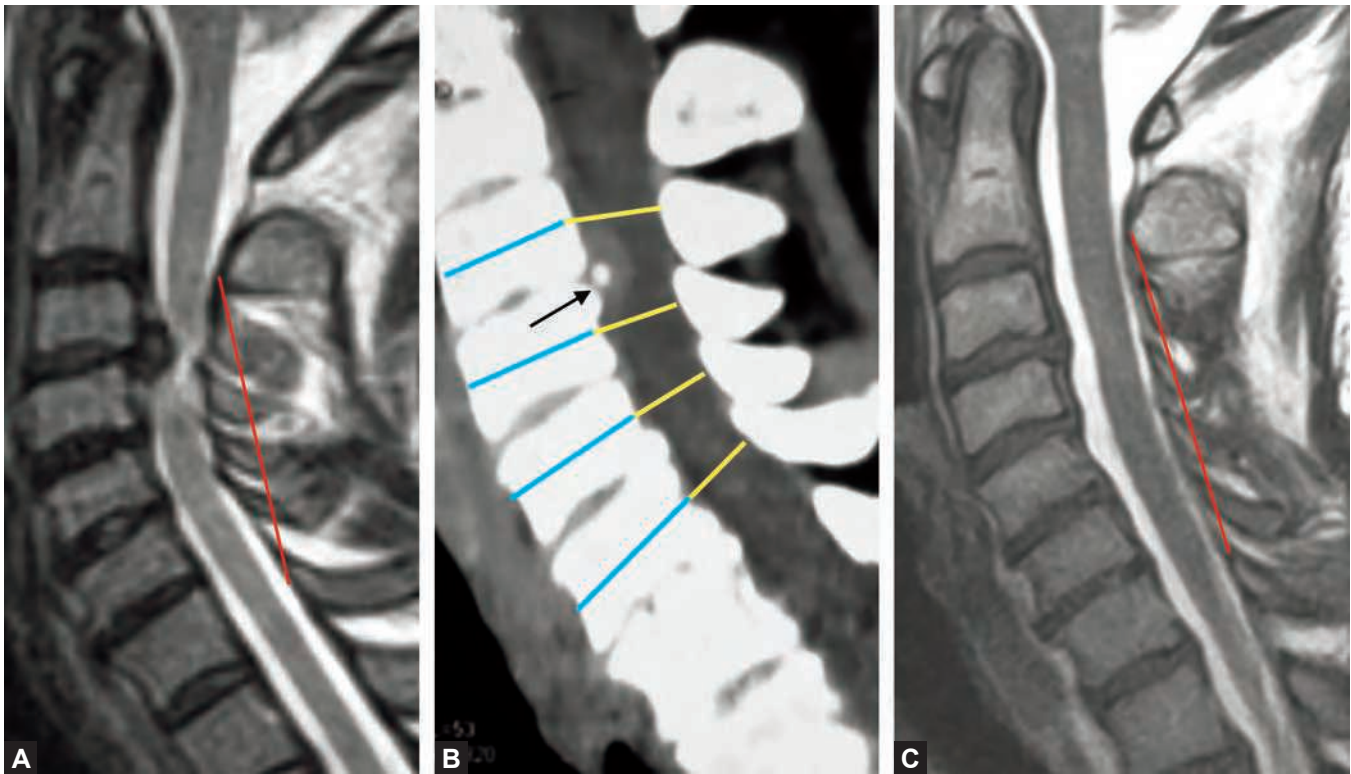
Laminectomy and Fusion

Kyphosis and instability following an isolated cervical laminectomy has led to many authors recommending a fusion if a laminectomy is performed.²¹ Early reports on the clinical outcomes of fusions performed with either

uninstrumented or instrumented (sublaminar wiring) techniques demonstrated good clinical outcomes.^{36,37} Kumar et al. reported on the outcomes of 25 patients treated for CSM by laminectomy, and lateral mass screw and plating with at least 2-year follow-up and reported no development of kyphosis or instability with 76% having improved myelopathy scores.³⁸ Houten et al. also found that at 30-month follow-up, no changes in cervical alignment occurred between the preoperative and 5.8-month follow-up X-rays.³⁹ The JOA score improved in 97% of patients from a mean of 12.9 preoperatively to 15.6 postoperatively.³⁹ Other authors have reported up to a 97% fusion rate with laminectomy and fusion with lateral mass screw and plate fixation at a mean of 15-month follow-up.⁴⁰ Contemporary techniques for cervical fusions include the



Figs. 43.14A to F: A 76-year-old male with minimal neck pain and a two years history of problems with fine motor skills, diffuse trunk numbness and bilateral upper extremity weakness. Magnetic resonance imaging (MRI) (A and B) and computed tomography (CT) (C) demonstrate a large calcified disk fragment with severe cord compression at C3/4 with simultaneous diffuse stenosis. (D) The patient underwent a Stage I: C3–C7 laminoplasty followed by a Stage II: C3–C5 ACDF, C4 hemicorp. (E and F) Postoperative computed tomography demonstrating resolution of C3/C4 compression and a wider central canal from C3–C7.



Figs. 43.15A to C: (A) Magnetic resonance imaging (MRI) demonstrating a C3/C4 disk herniation. (B) Computed tomography (CT) scan showing a concomitant C3/C4 ossified disk fragment. (black arrow). (C) 6 months s/p C3-C6 laminoplasty with a postoperative MRI demonstrating resolution of the disk fragment.

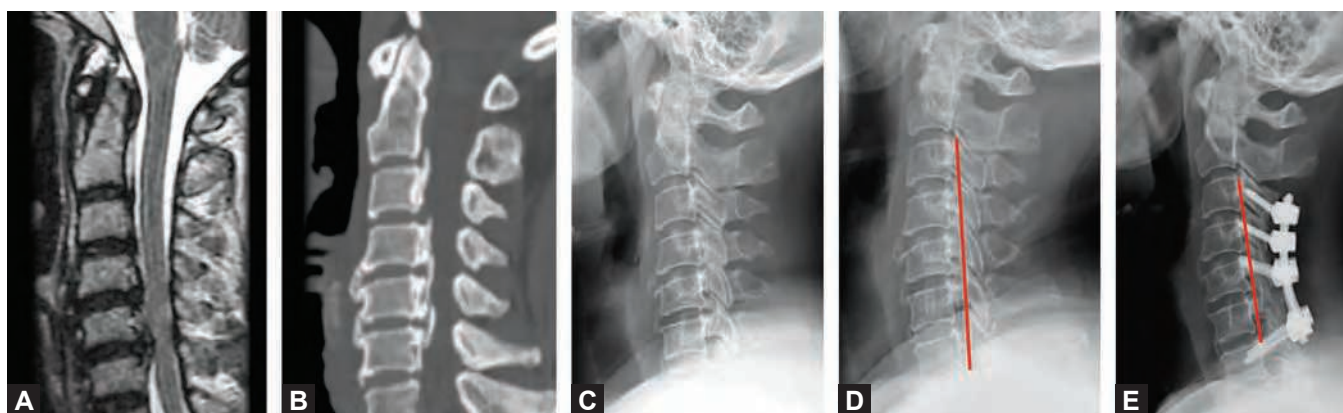
use of lateral mass screw and rod fixation. The use of lateral mass screws has been associated with a considerably low rate of complications even in the setting of bicortical screw purchase.⁴¹ Complications include nerve root injury (0.6%), facet violations (0.2%), broken screws (0.3%), screw loosening (1.1%), infection (1.3%), and pseudarthrosis (1.4%).⁴¹ It is our preference to instrument the subaxial spine with lateral mass screws and rods and this is the technique that will be reviewed in this section. It should be noted that at the time of this publication the use of lateral mass and pedicle screws in the cervical spine is not approved by the US Food and Drug Administration.

Indications for a laminectomy and fusion include those patients who cannot undergo a laminoplasty because of kyphosis, instability, or resection of >50% of the facets during foraminotomies. Patients who undergo a laminectomy and fusion still need to have lordosis at the completion of the fusion. This means that patients who are able to achieve lordosis on extension but have neutral alignment on a lateral view are good candidates for a fusion as the fusion can hold the patient in lordosis. In patients with neutral alignment or slight kyphosis, the neck can

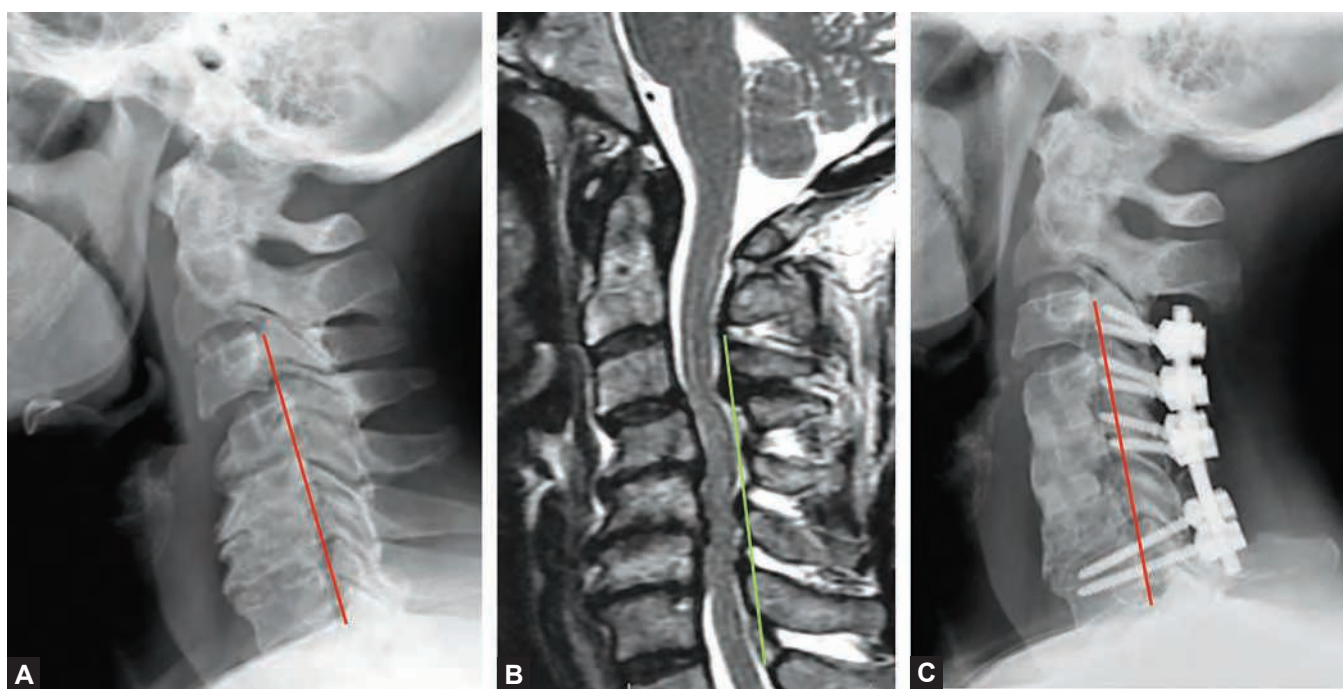
be positioned and fused in lordosis once the laminectomy is completed prior to locking the rod to the screws (Figs. 43.16A to E). However, in the setting of significant kyphosis or instability, an anterior posterior procedure may need to be performed. Multilevel ACDFs either instrumented or uninstrumented can be used to create anterior column support and lordosis. Once lordosis is achieved, a posterior laminectomy and fusion can then be performed (Figs. 43.17A to C).

The levels chosen for the laminectomy typically include all of the stenotic levels seen on imaging studies. In order to prevent distal junctional kyphosis, the distal extent of the fusion is carried out one additional level past the last laminectomy level. For example, a C3-C6 laminectomy should be combined with a C3-C7 fusion. Some authors advocate not stopping the fusion at C7, as it leaves the cervicothoracic junction open. It is our experience that in the setting of instability at C7/T1, the fusion should be carried to T1. It is currently our preference to carry the distal extent of the fusion to T1 in most cases.

The surgical technique begins in a similar patient position as the laminoplasty. Exposure needs to include the



Figs. 43.16A to E: (A to D) A 47-year-old Asian female with left sided weakness and myelopathy. Magnetic resonance imaging (MRI) and computed tomography (CT) demonstrating stenosis and ossification of the posterior longitudinal ligament (OPLL). Neutral radiograph demonstrates neutral alignment and loss of normal lordosis. Extension X-ray demonstrates ability to achieve lordosis. (E) C3 to C6 laminectomy and C3 to C7 fusion with maintenance of lordosis with the fusion.



Figs. 43.17 A to C: (A) A 66-year-old female with myelopathy. Neutral X-ray with loss of lordosis. (B) Magnetic resonance imaging (MRI) with central stenosis and a negative posterior spinal line in green. (C) Stage 1: Anterior cervical discectomy and allograft placement at C4/C5 and C5/C6. Stage 2: Posterior cervical laminectomy and fusion from C3 to C7 with lateral mass and pedicle screw instrumentation.

lateral aspect of each lateral mass and facet joints to be fused. We prefer to drill and prepare the holes for each lateral mass prior to the laminectomy to avoid passing instruments over an exposed spinal cord. A 2-mm round burr is then used to decorticate each facet joint. The center of each lateral mass is identified, and a 2-mm round burr is used to make a pilot hole. A drill with a 14 mm stop is

then used at the starting point and drilled in an upward and outward technique according to the Roy Camille technique. Typically, the appropriate angulation involves the drill touching the spinous process of the inferior vertebrae being instrumented. Some surgeons prefer to place lateral mass screws in a bicortical manner. In this situation, a depth stop is not used as the surgeon has a tactile

sensation when crossing the second cortex of the lateral mass. It should be noted that the exiting nerve is at risk when placing a bicortical screw (i.e. C5 nerve with a C5 lateral mass screw). A ball tip feeler can be used to confirm that each drilled hole has four walls prior to screw placement. Liquid gelfoam or Floseal can also be pressurized into the tapped hole to ensure that it has a floor. Extravasation around the lateral mass or into the facet joint indicates that there may be a bony defect present. It is our preference to tap each hole prior to screw placement to avoid cracking the lateral mass during screw insertion. Pedicle screws are typically placed at the distal extent of the fusion (C7 or T1 pedicle screw). This chapter is covered elsewhere in this book.

Once the screw holes are prepared, the laminectomy is performed. The width of the laminectomy is based on the width of the spinal cord measured from axial MRI and CT images and is typically 18 mm. The width of the laminectomy can be set with calipers and marked using a surgical marker on the lamina as a guide. The laminectomy is then performed using an AM-8 acorn tip burr. The outer lamina, cancellous bone, and inner lamina can be drilled up until the ligamentum flavum. A 1-mm Kerrison can then be used to scissor up the troughs to separate the flavum from the dura. At this point, the lamina should be removed as one unit in an en bloc manner. This is performed by taking towel clamps and attaching them to each spinous process. The lamina is removed from caudal to cranial using a large angled ball tip probe to separate dural adhesions from the lamina. It is typically difficult to separate the laminar block at C2-C3 (for a C3-C7 laminectomy) from C2. Gently placing pressure inferiorly on the block of lamina can typically unshingle and separate the C3-C7 lamina from C2. Hemostasis can be achieved with liquid gelfoam.

Once the laminectomy is performed, the lateral mass screws typically (3.5 mm by 14 mm) are placed in the prepared holes. At this point, the surgeon should unscrub and position the neck in lordosis using the Mayfield tongs and table clamps. The degree of lordosis can be assessed using fluoroscopy. Contoured lordotic rods are then final tightened to the tulip heads. Local autograft bone from the posterior elements is ground and mixed with allograft and placed over the decorticated lateral masses and facet joints. Patients are instructed to wear a rigid, semirigid collar or soft collar for at least 6 weeks postoperatively.

OUTCOMES

There are few clinical studies comparing the treatment of anteriorly versus posteriorly based procedures for CSM.

Fang et al. reported on the clinical and radiologic outcomes between expansion open-door laminoplasty with foraminotomy and ACDF in the treatment of coexisting multilevel CSM and unilateral radiculopathy.⁴² A total of 110 patients were followed for >3 years, and in the laminoplasty group, there was shorter operative time, less blood loss, and fewer complications than the ACDF group. Both groups had similar neurological recover based on JOA scores.⁴² There are few clinical studies comparing posteriorly based procedures. Yukawa et al. reported on the results of one prospective randomized study comparing laminoplasty to skip laminectomy.⁴³ Patients in both groups had 80% of the preoperative ROM in both groups, and there were no differences in JOA scores or axial neck pain.⁴³ In a small matched cohort study, Heller et al. compared 13 patients who had laminoplasty to 13 patients with laminectomy and fusion for multilevel CSM with approximately 2-year follow-up. The laminoplasty group had greater subjective improvement in strength, dexterity, sensation, pain, and gait.⁴⁴ Interestingly, the presence of axial neck pain was the same in both groups.⁴⁴ Yoon et al. performed a systematic review comparing outcomes of laminoplasty versus a laminectomy and fusion.⁴⁵ For patients with CSM, there is evidence that suggests that laminoplasty and laminectomy and fusion procedures are similarly effective with similar safety profiles. Higher-quality research is necessary to more clearly delineate when one procedure is preferred compared with the other.⁴⁵

COMPLICATIONS

Other than hardware complications, postoperative C5 nerve root palsy is one of the most common neurological complications. A C5 palsy presents as deltoid or biceps weakness and typically presents in the first postoperative week though it has been reported to vary between immediately to up to 2 months after surgery.⁴⁶ C5 palsy has been reported with both anterior and posterior procedures and is postulated to be secondary to traction on the C5 nerve from spinal cord float. Dai et al. reported a rate of 12.9% following a laminectomy with the most frequent pattern being C5 or C6; the mean time for recovery was 5.4 months.⁴⁷ Bydon et al. examined the incidence and prognostic factors of C5 palsy in 1001 anterior and posterior cases and reported an 8.6% incidence in posterior procedures.⁴⁸ After approximately 2 years, C5 palsies improved in 89% of patients. Older age was the strongest predictor of C5 palsy.⁴⁸ In a large scale systematic review, Gu et al.

found that risk factors for a C5 palsy include patients with excessive spinal cord drift, pre-existing foraminal stenosis, OPLL, laminectomy (rather than laminoplasty), and male gender.⁴⁶ Katsumi et al. studied the characteristics of the foramen in patients with and without a C5 palsy in 141 patients who underwent a laminoplasty.⁴⁹ They reported that the average diameter of the C4/C5 foramen was 1.99 mm in the palsy group and 2.76 mm in the nonpalsy group, suggesting that the etiology of C5 palsy is impairment of the C5 nerve root induced by pre-existing C4/C5 foraminal stenosis.⁴⁹ The same group evaluated the effectiveness of a prophylactic C4/C5 foraminotomy with open-door laminoplasty in 141 patients with CSM and found that the incidence of C5 palsy was 1.4% in the foraminotomy group versus 6.4% in the nonforaminotomy group.⁵⁰ They concluded that a prophylactic foraminotomy was an effective preventive measure against postoperative C5 palsy after laminoplasty.⁵⁰ Since the majority of C5 palsies resolve, treatment involves patient education as well as passive ROM of the shoulder to prevent a frozen shoulder. There is no data regarding use of epidural or systemic steroids to prevent or shorten the course of C5 palsy. In the setting of a very dense C5 palsy, some surgeons perform a C4/C5 foraminotomy postoperatively to try to give the nerve as much room as possible to recover.

It is critical to limit the width of the laminectomy in a laminectomy fusion procedure to the width of the spinal cord (18 mm). A wider laminectomy and greater posterior cord drift has been associated with an increased risk of postoperative C5 palsy in multiple clinical studies.^{51,52} The laminectomy width is typically greater in laminoplasty procedures, as the laminoplasty trough is made from one lamina-facet junction to another. We currently perform a C4/C5 foraminotomy either through an ACDF or a posteriorly when a laminectomy/fusion or laminoplasty is performed in the setting of a pre-existing stenotic C4/C5 foramen.

KEY POINTS

- A posterior procedure for CSM is ideally performed in the presence of a lordotic spine so the spinal cord can float away from the posterior elements once released. However, if the PSL indicates that there are compressive elements anterior to it, then a posterior approach may be considered despite the presence of kyphosis with the understanding that the cord will be realigned in the canal.

- A laminectomy alone without a fusion is generally not recommended secondary to the risk of postlaminectomy kyphosis. Ideal patients for a laminectomy alone have a very spondylotic or ankylosed spine to minimize the risk of kyphosis and instability.
- Patients who are candidates for a laminoplasty have a neutral to lordotic spine, minimal spondylosis, and a congenitally small canal. The laminoplasty trough (22–24 mm) should be wider than a laminectomy trough (18 mm) and is measured from one lamina-facet junction to the other. Reconstruction with spacers and miniplates is preferred following a laminoplasty for stability.
- Patients who do not have lordosis but can achieve lordosis on an extension radiograph are candidates for a laminectomy and fusion. Significant kyphosis can be corrected with multilevel ACDFs followed by a posterior laminectomy and fusion. The distal fusion level should be one level below the last laminectomy level to prevent distal junctional kyphosis.
- A postoperative C5 palsy is the most common complication and can be minimized by performing a C4/C5 foraminotomy during the posterior procedure if there is pre-existing foraminal stenosis. In the setting of a laminectomy and fusion, a postoperative C5 palsy can be minimized by limiting the laminectomy width.

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Natural History and Surgical Treatment for Ossification of the Posterior Longitudinal Ligament

Kraig Kristof, Jeffrey S Fischgrund

Snapshot

- » Pathogenesis
- » Natural History
- » Classification
- » Clinical Presentation
- » Conservative Management
- » Surgical Treatment of Cervical OPLL
- » Surgical Treatment of Thoracic OPLL
- » Surgical Management of Lumbar OPLL
- » Surgical Complications

INTRODUCTION

Ossification of the posterior longitudinal ligament (OPLL) involves pathologic calcification of the posterior longitudinal ligament anywhere along the length of the spinal column with the cervical region being the most commonly affected. Because it is a space occupying lesion within the spinal canal, the spinal cord may be compressed leading to various neurologic deficits with cervical myelopathy being the most common. Patients with overt neurologic manifestations of OPLL are usually treated with decompression of the spinal cord from either an anterior or posterior approach, with some patients needing a combined procedure. Although the exact pathogenesis and natural history are not fully elucidated, there have been great strides in these areas over the recent years.

Tsuyama, has reported on the incidence of OPLL: 2.4% in Asian populations and 0.16% in non-Asian populations. The highest rates of OPLL are found in Japan and it is more than twice as common in men than women, with symptomatic OPLL usually presenting in the 5th to 6th decade of life. Ossification of the posterior longitudinal ligament was previously considered to be specific to Asian people but now some studies believe OPLL is a subtype of diffuse idiopathic skeletal hyperostosis,²⁻¹⁰ which is well known

in the United States and Europe. There have also been reports of OPLL in conjunction with ankylosing spondylitis and other spondyloarthropathies.^{11,12} Other patient populations have also shown the development of OPLL. Maiuri et al.¹³ reported on eight Italian patients with OPLL and Matsunaga et al.¹⁴ reported a 20% incidence in patients with schizophrenia.

In terms of the pathology of OPLL, it is believed to form through endochondral ossification. The histopathology was described by McAfee et al.⁹ in which OPLL is composed mostly of lamellar bone with mature Haversian canals. The study of the ligamentum flavum in patients with OPLL revealed atrophic elastic bundles with a two-layer structure, disappearance of microfibrils, irregular alignment of collagen fibrils, and many extracellular plasma membrane-invested particles that resemble matrix vesicles.¹⁵

PATHOGENESIS

Numerous studies have examined the poorly understood pathogenesis of OPLL. Results point to a combination of genetic and environmental factors that contribute to the formation of OPLL. Ishida and Kawai¹⁶ studied cell lines from nonossified sites in patients with OPLL and

Table 44.1: Summary of notable genes, transcription factors, and cytokines implicated in ossification of the posterior longitudinal ligament pathogenesis.

Gene	Protein	Chromosome	Physiological function
<i>NPPS</i>	Nucleotide pyrophosphatase	6	Regulates soft-tissue calcification and bone mineralization via the production of PPi, a known inhibitor of calcification
<i>COL11A2</i>	$\alpha 2$ chain, Type XI collagen	6	Associates w/Type II collagen and is responsible for forming the size, diameter and growth rate of fibril networks, forms extracellular matrix scaffolds and may contribute to the formation of ectopic bone by enhancing endochondral ossification
<i>COL6A1</i>	$\alpha 1$ chain, Type VI collagen	21	Forms extracellular matrix scaffolds and may contribute to the formation of ectopic bone by enhancing endochondral ossification
<i>BMP-2</i>	BMP-2	20	Stimulates proteoglycan formation and alkaline phosphatase activity in chondroblasts and osteoblasts and defects cellular differentiation
<i>TGFβ</i>	TGF β 1	19	Mediates bone development and metabolism

Source: Stapleton CJ, Pham MH, Attenello FJ, et al. Ossification of the posterior longitudinal ligament: genetics and pathophysiology. *Neurosurg Focus*. 2011;30(3):E6.

found that they have high alkaline phosphatase activity, response to calcitonin, and calcitriol. An immunohistochemical study of extracellular matrix in the twy mouse (tiptoe walking Yoshimura—an animal model for OPLL) shows that degeneration and subsequent herniation of the intervertebral disc is a significant factor in initiating OPLL formation. At 14 weeks, the discs that herniated into the thickened posterior longitudinal ligament caused cartilaginous tissue to form within the ligament, as if to repair the disc degeneration.¹⁷

Hypertrophy of the posterior longitudinal ligament is also thought to be an early stage of OPLL. One study showed that the hypertrophied ligament exhibited very similar characteristics of OPLL in terms of hyaline degeneration, proliferation of chondrocytes and fibroblast-like spindle cells, infiltration of vessels and small ossification, and staining by BMP, TGF- β , and proliferating cell nuclear antigen.¹⁸

Numerous genetic factors have been implicated in the formation of OPLL (Table 44.1).¹⁹ The proteins made from these genes have been shown to be crucial in the regulation of chondrogenesis, osteogenesis, or bone mineralization. Okawa et al.^{20,21} performed a genetic analysis of two mice and found a single-base mutation in the *NPPS* gene that results in loss of more than one-third of the native *NPPS* enzyme. Nucleotide pyrophosphatase (*NPPS*) is a type II transmembrane metalloenzyme that regulates soft-tissue calcification and bone mineralization via the production of PPi,²² a known inhibitor of calcification.²³ There are at least three isoforms of *NPPS* in humans with the *NPP1* subtype being implicated in OPLL pathogenesis.²⁴

This subtype generates PPi in osteoblasts and chondrocytes and regulates bone mineralization by decreasing hydroxyapatite crystal deposition.²³ Although not fully understood, when extracellular PPi levels are low, pathologic calcification of ligaments and joints occur. In a later study by Tahara et al.,²⁵ the authors showed that *NPPS* and leptin receptor genes do not promote an increased susceptibility to OPLL, but are associated with the extent of heterotopic ossification. Horikoshi et al.²⁶ also could not demonstrate the association between the *NPPS* gene and OPLL.

Many collagen genes have also been studied, including human collagen $\alpha 2$ gene (*COL11A2*). Koga et al.²⁷ showed that this gene, located on chromosome 6p close to the human leukocyte antigen region, is strongly associated with OPLL. Retaining exon 7 together with removal of exon 6 in the *COL11A2* gene could play a protective role in the ectopic ossification process.²⁸ Maeda et al.²⁹ reported a sex specific association of the *COL11A2* haplotype with OPLL in male patients. However, a recent study by Horikoshi et al.²⁶ could not reproduce the association between this gene and OPLL.

A single nucleotide polymorphism in the collagen 6A1 gene (*COL6A1*) has been shown to be associated with OPLL.^{30,31} Kong et al.³² studied the Han Chinese population and found a significant association of *COL6A1* with OPLL. They demonstrated that three single-nucleotide polymorphisms are significantly associated with the formation of OPLL and ossification of the ligamentum flavum.

Bone morphogenetic protein, BMP-2, a substance with the ability to induce ectopic bone, is believed to play an important role in the pathogenesis of OPLL. Bone

morphogenetic protein receptors are increased in ossified ligament tissue in patients with OPLL.³³ Bone morphogenetic protein-2 stimulates differentiation of ligament cells in patients with OPLL, and both induces ossification by increasing alkaline phosphatase activity and stimulating DNA and procollagen type I carboxyl-terminal peptide synthesis.³⁴ The TC and CC genotypes in the BMP-2 gene of male Han Chinese patients have a genetic susceptibility to OPLL in the cervical spine.³⁵

Transforming growth factor- β has also been studied in the literature. The T869°C polymorphism of the TGF- β 1 gene is a genetic determinant of a predisposition to OPLL.³⁶ Kawaguchi et al.³⁷ later demonstrated that the TGF- β 1 polymorphism is not associated with OPLL development, but rather a factor related to the extent of ossification. Patients with the T869°C allele polymorphism frequently have OPLL in the cervical, thoracic, and/or lumbar spine.

In addition to the above genetic products influencing OPLL, numerous other studies have shown various biomarkers that were upregulated in the sera of OPLL patients.^{33,38-43} There is also evidence that noninsulin-dependent diabetes mellitus may be a risk factor of OPLL.⁴⁴

Environmental factors have also been implicated in the formation of OPLL. Mechanical stress in ligaments of the spine has been investigated as a cause of OPLL development and progression.⁴⁵ Prostacyclin synthase levels in ligament cells from OPLL patients have been shown to be elevated after applying mechanical stress and induced osteogenic differentiation via the PGI₂/cyclic adenosine monophosphate pathway.⁴⁶ Mechanical stress also induces mRNA expression of alkaline phosphatase, osteopontin, BMP-2, BMP-4, BMP receptors,⁴⁷ and mRNA expression of Cbfa1, type I collagen, osteocalcin, integrin β 1,⁴⁸ and endothelin-1.⁴⁹ The P2Y1 purinoceptor subtypes, intensively expressed in OPLL cells, responded to mechanical stress induced extracellular adenosine triphosphate, which stimulated OPLL progression.⁵⁰

Other environmental associations with OPLL include frequent consumption of pickles, nondaily consumers of rice,⁵¹ family history of myocardial infarction, high body mass index at age 40, long working hours, and working night shifts.⁵² In contrast, frequent consumption of chicken and soy products⁵³ and proper sleeping habits (6–8 hours/night) in the prime of life may decrease the risk of OPLL.

■ NATURAL HISTORY

The natural history of OPLL was investigated by Matsunaga et al.⁵⁴ in which 450 patients with OPLL were followed for at

least 10 years with a mean follow-up of 17.6 years. Only 17% of patients without myelopathy at the first visit developed myelopathy during the follow-up period. The myelopathy-free rate in these patients was 71% after 30 years according to Kaplan–Meier analysis. The researchers suggested that prophylactic surgery in patients without symptoms of myelopathy is unnecessary. This same group of authors⁵⁴ studied predictors for development of myelopathy in 156 patients with OPLL from 16 spine institutes with an average follow-up period of 10.3 years. They found that both static and dynamic factors were related to the development of myelopathy.³⁹ Patients with >60% spinal canal stenosis on plain radiography developed myelopathy. They concluded that 60% spinal canal stenosis by OPLL and lateral deviated-type OPLL on computerized tomography (CT) scan (Figs. 44.1A to C) were radiographic risk factors for development of myelopathy. Range of motion was also significantly greater in patients with myelopathy.

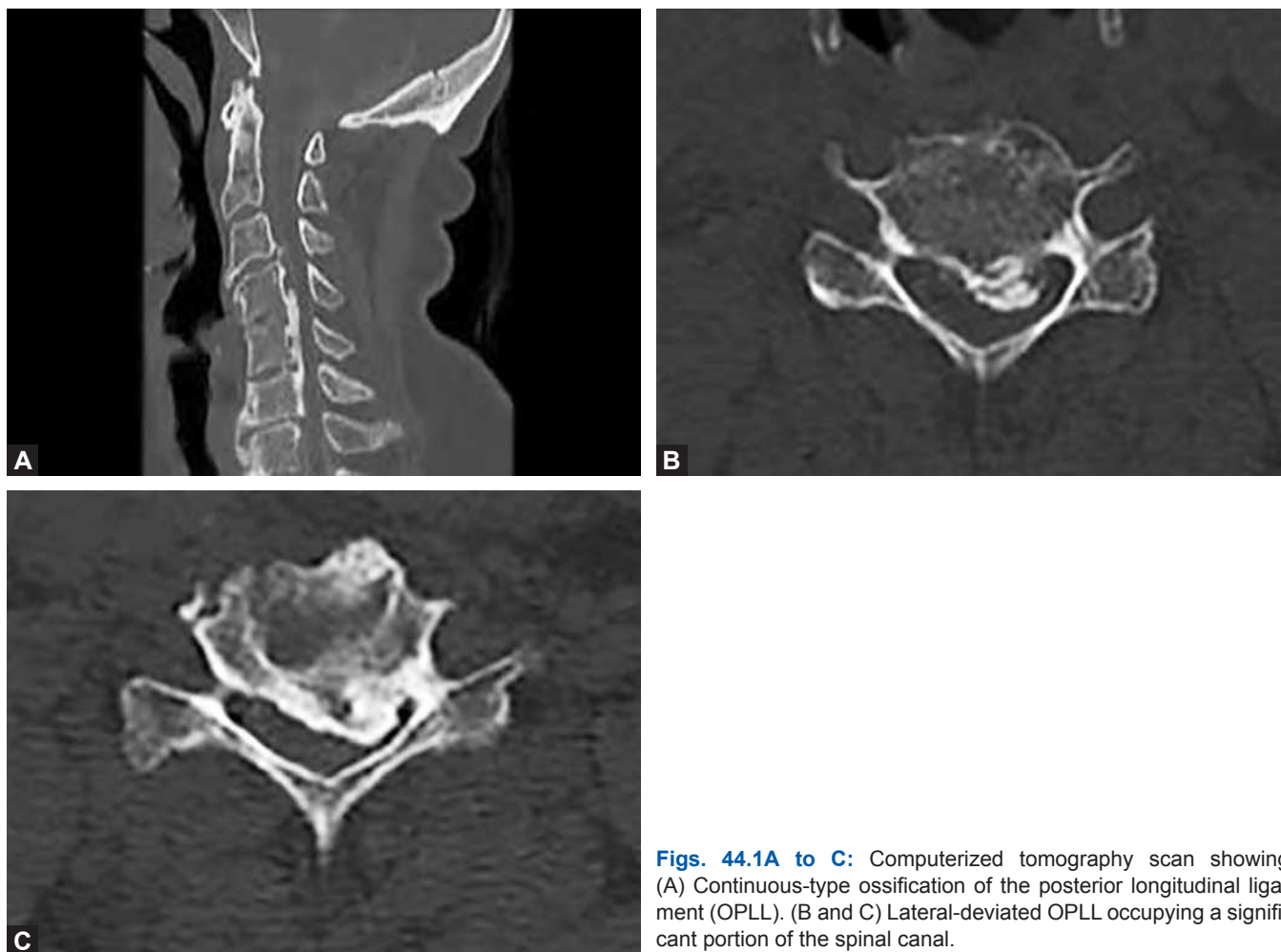
Both Chiba et al.⁵⁵ and Hori et al.^{56,57} looked at progression of OPLL. Both found that progression was more common in younger patients with continuous- and mixed-type OPLL.

■ CLASSIFICATION

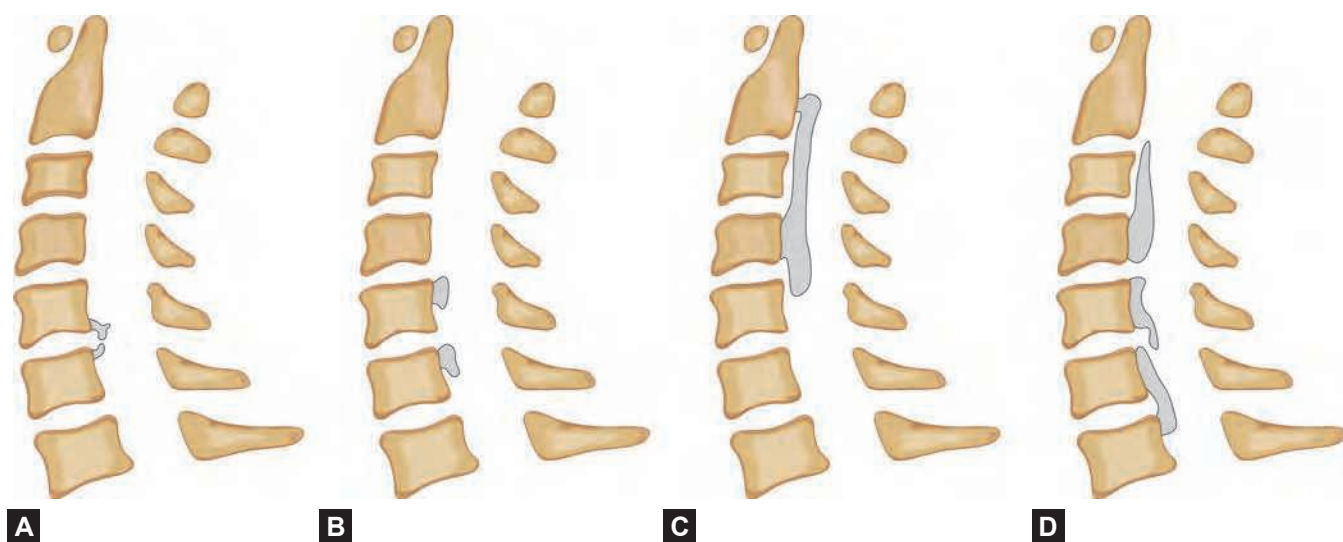
The Investigation Committee on OPLL of the Japanese Ministry of Public Health and Welfare described the OPLL classification that is most widely used in the literature.⁵⁸ Based on lateral plain radiography, cervical OPLL can be classified into four types (Figs. 44.2A to D)⁵⁹: continuous, segmental, mixed, or circumscribed type. Continuous type is classified as a long lesion extending over several vertebral bodies. Segmental type is classified as one or several separate lesions behind the vertebral bodies. Mixed type is classified as a combination of continuous and segmental types. Circumscribed type is classified as the lesion mainly located posterior to a disc space.

■ CLINICAL PRESENTATION

Early in the course of the disease, most OPLL patients are asymptomatic, have mild pain and discomfort, or complain of mild numbness in their hands. As the OPLL lesion progresses, symptoms increase in severity due to compression of the spinal cord and/or nerve roots. Various presentations of OPLL occur from hand dysesthesia and tingling to hand clumsiness and gait disturbance with frank myelopathy. About 80–85% of OPLL patients experience a



Figs. 44.1A to C: Computerized tomography scan showing (A) Continuous-type ossification of the posterior longitudinal ligament (OPLL). (B and C) Lateral-deviated OPLL occupying a significant portion of the spinal canal.



Figs. 44.2A to D: (A) Circumscribed type. (B) Segmental type. (C) Continuous type. (D) Mixed type. Cervical ossification of the posterior longitudinal ligament.



Figs. 44.3A and B: (A) Plain radiograph showing continuous-type ossification of the posterior longitudinal ligament (OPLL); (B) Computerized tomography scan showing extensive OPLL involvement over multiple levels and amount occupying a significant portion of the canal.

slow progression, but even relatively mild injuries may suddenly aggravate symptoms or even cause quadriplegia.

Radiological Evaluation

Plain radiography is the most basic method for detecting OPLL, but it is very limited in its ability to pick up all cases or the extent of ossification. Chang et al.⁶⁰ reported that lateral radiography has poor inter- and intraobserver reliability for OPLL classification, especially for continuous-type OPLL.

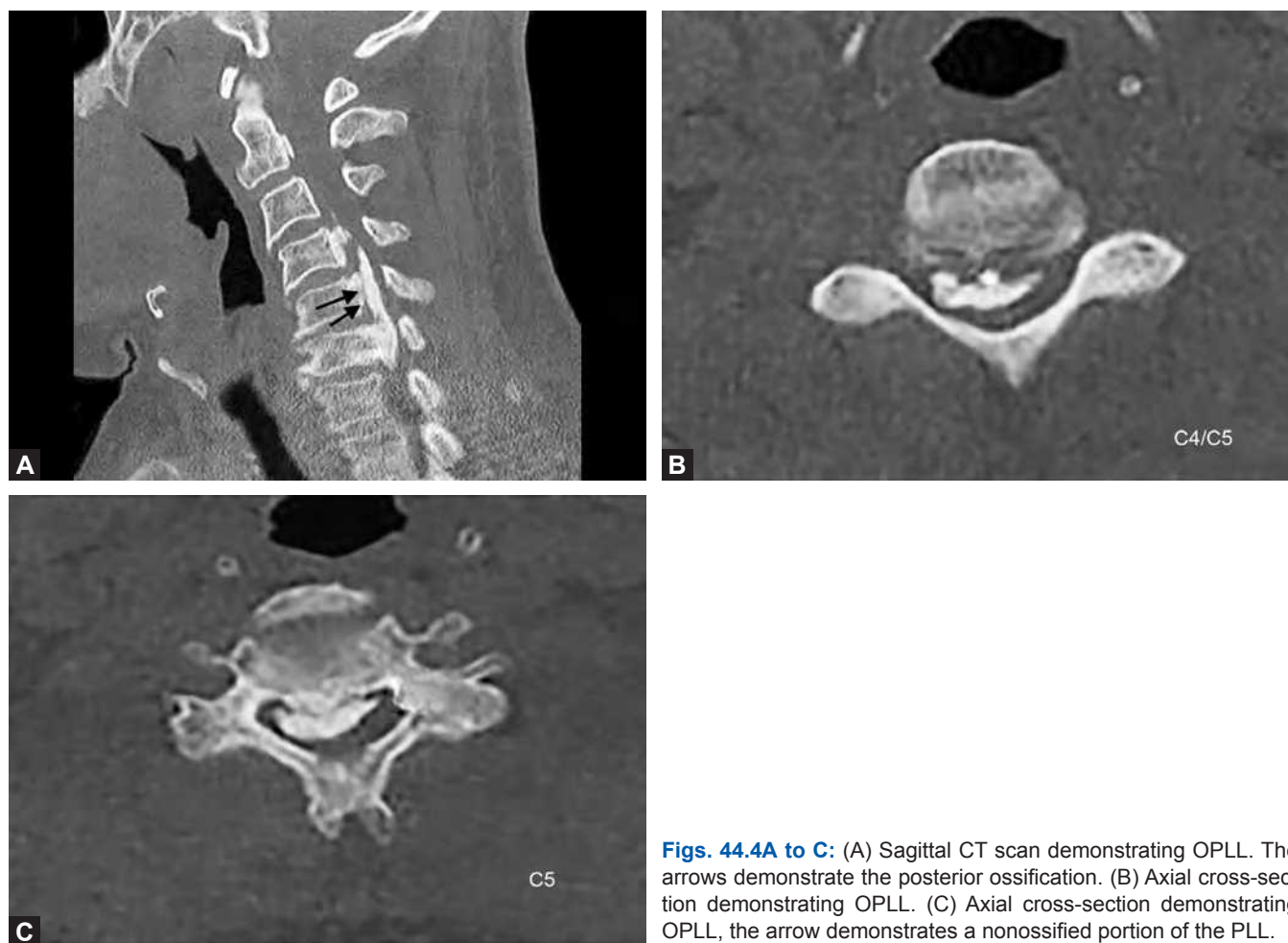
Computed tomography with or without myelography is the most useful study to show the extent and location of OPLL. It accurately depicts the severity of canal stenosis and the exact dimensions of the disease (Figs. 44.3A and B). Axial CT scan characteristically shows a sharp radiolucent line between the posterior vertebral body and the ossified ligament as well as a hill or mushroom shape of ossification.⁶¹

Dural ossification poses a particular problem in OPLL because anterior decompression may have a significant incidence of new neurological deficits and iatrogenic cerebrospinal fluid (CSF) leak. Computerized tomography scan is useful in detecting dural ossification, preoperatively. A retrospective review performed by Mizuno et al.⁶² evaluated the relationship between dural ossification and preoperative imaging. Bone window CT scans were found to be the best method for detecting dural ossification

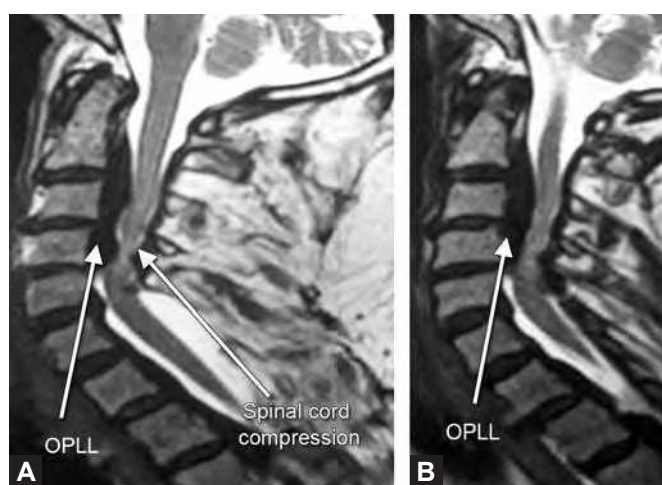
and magnetic resonance imaging (MRI) was found to be ineffective. Nonsegmental type was found to be the most likely to have dural ossification. Two types of dural ossification patterns, double- and single-layer sign, were described by Hida et al.⁶³ based on the bone window CT images. Single layer sign was defined as a large focal mass of uniformly hyperdense OPLL. Double-layer sign was defined as anterior and posterior rims of hyperdense ossification separated by a central hypodense mass (Figs. 44.4A to C). This hypodense mass is the hypertrophied but nonossified posterior longitudinal ligament. Dural defects, during surgical decompression, were detected in 10 of 12 patients with double-layer sign and only 1 of 9 patients with single-layer sign. This finding was confirmed by Epstein;⁶⁴ a single layer sign indicated a clean dural plane with a low incidence of dural defect. Min et al.⁶⁵ studied cervical OPLL in 197 patients who underwent anterior decompression and fusion. This study also served to confirm the importance of the double-layer sign indicating dural ossification with 20 of 38 patients having dural defects and only 3 of 22 patients having defects with single-layer sign.

Min et al.⁶⁶ also found that dural ossification is even more common in thoracic OPLL with a rate of 80%. They also showed that dural ossification was detected in both nonsegmental and segmental types in the thoracic spine. Magnetic resonance imaging is sensitive for detecting soft tissue abnormalities, but is not adequate for diagnosing small ossified lesions in the spinal canal.⁶⁷ Ossification of the posterior longitudinal ligament is hypointense on both T1- and T2-weighted MRI. Characteristic findings on MRI are shown in Figures 44.5A and B. Koyanagi et al.⁶⁸ found that disc protrusion was found at the maximal compression level in 60% of patients with cervical OPLL and is more common in segmental OPLL, with an incidence of 81%. It was concluded that MRI is useful for determining the level of spinal cord compression and for helping determine the best method of surgical treatment.

Signal hyperintensity of the spinal cord on T2-weighted images were correlated with more severe neurological deficit in patients with OPLL.⁶⁸ In another study, Yagi et al.⁶⁹ found a positive correlation between postoperative expansion of the high signal intensity area of the cord and poor neurological outcome of patients with cervical OPLL. Spinal instability was found to be a risk factor for this expansion. Magnetic resonance imaging is also useful for determining the cross-sectional shape of the spinal cord at the level of maximum compression. Three shapes were



Figs. 44.4A to C: (A) Sagittal CT scan demonstrating OPLL. The arrows demonstrate the posterior ossification. (B) Axial cross-section demonstrating OPLL. (C) Axial cross-section demonstrating OPLL, the arrow demonstrates a nonossified portion of the PLL.



Figs. 44.5A and B: T2 magnetic resonance imaging showing low signal intensity of the ossification of the posterior longitudinal ligament (OPLL) lesion and significant compression of the spinal cord with increased signal intensity at the point of maximal compression. (A and B) Severe spinal cord compression and OPLL.

classified by Maysuyama et al.⁷⁰ as boomerang, teardrop, or triangular. The recovery rate after laminoplasty was the worst for patients with a triangular shape and the best for the teardrop shape. The boomerang shape was intermediate. The triangular shape had the least expansion postoperatively that correlated with a poor outcome.

Ossification of the posterior longitudinal ligament has also been described to occur at multiple locations. Park et al.⁷¹ found thoracic tandem ossification in 23 out of 68 patients with cervical OPLL. The authors recommended imaging the thoracic spine in any patient undergoing cervical OPLL surgery.

CONSERVATIVE MANAGEMENT

Although surgical treatment is the mainstay of treatment for moderate-to-severe OPLL with myelopathy, observation is an option in asymptomatic or mildly symptomatic

Table 44.2: Advantages and disadvantages of surgical procedures for cervical OPLL.

<i>Surgical procedure</i>	<i>Advantages</i>	<i>Disadvantages</i>
Laminectomy	Simple, less operative time and blood loss, low immediate complication	Risk of OPLL progression; risk of kyphotic deformity, spinal instability, and neurological deterioration due to scar tissue formation; ineffectiveness in cases w/severe kyphotic deformity and large OPLL
Laminectomy w/fusion	Relatively simple, low complication rate, decreased risk of kyphotic deformity and spinal instability	Risk of OPLL progression, ineffectiveness in cases w/severe kyphotic deformity and large OPLL
Laminoplasty	Relatively simple, low complication rate compared w/ant approach, decreased risk of kyphotic deformity, spinal instability and neurological deterioration due to scar tissue formation compared w/laminectomy alone	Risk of OPLL progression, limited effectiveness in cases w/severe kyphotic deformity and large OPLL
Ant approach	Direct ant decompression of OPLL	High complication rate (particularly neurological deterioration, graft complication, and CSF leakage), limitation in cases w/long segment OPLL or OPLL involving C-2
Combined Ant and Post approach	Direct and decompression of OPLL	More operation time and blood loss

(OPLL: Ossification of the posterior longitudinal ligament, Ant: Anterior, Post: Posterior).

Source: Saetia K, Cho D, Lee S, et al. Ossification of the posterior longitudinal ligament: a review. *Neurosurg Focus*. 2011;30(3):E1.

patients. Pham et al.⁷² evaluated the conservative management of OPLL. They discovered that patients who present without myelopathy have a high chance of remaining progression free; however, those who already have signs of myelopathy at presentation may benefit from surgery due to a high rate of progression over continued follow-up. Effective medical treatment is still lacking for OPLL and further research is needed to elucidate targets of medical therapy. Currently, there are only symptomatic treatments such as pain medications, anti-inflammatory drugs, antidepressants, and anticonvulsants as well as rest, physical therapy, and soft collar.

SURGICAL TREATMENT OF CERVICAL OPLL

The cervical spine is the most common location for OPLL; thus, there is an abundance of literature with various surgical techniques for treating the condition. Described techniques include the posterior approach (laminectomy, laminectomy with instrumented fusion, laminoplasty), the anterior approach [anterior cervical discectomy and fusion (ACDF), anterior cervical corpectomy with fusion, open-window corpectomy, oblique corpectomy, skip corpectomy, and anterior decompression via a transvertebral approach], and the combined anterior and posterior

approach. Table 44.2 summarizes the advantages and disadvantages of each approach.⁵⁹

Posterior Approaches

Laminectomy alone is the simplest approach to decompress the spinal cord. However, if fusion is not performed, progression of kyphotic deformity has been reported. The progression did not affect neurologic outcomes as shown in several studies.^{73,74} Kato et al.⁷⁴ also found that OPLL progressed in 70% of patients that underwent laminectomy alone, but it was only the cause a neurologic deterioration in one patient. There was also a rare reported case of incarcerated spinal cord herniation with neurologic deterioration after laminectomy in a patient with OPLL and ossification of the ligamentum flavum (OLF).⁷⁵

Laminectomy with fusion (Figs. 44.6A to J) in patients with at least 10° of lordosis decreases the risk of postoperative kyphotic deformity and instability, but the functional improvement is similar to laminectomy alone or laminoplasty.⁷⁶ Anderson et al.⁷⁶ described several posterior cervical fusion techniques with lateral mass and pedicle screws and found that there is a low risk of neurovascular injury. Houten and Cooper⁷⁷ demonstrated that laminectomy and posterior lateral mass fusion can result in high rates of fusion, preserved lordosis, and clinical results comparable or superior to those seen with anterior



Figs. 44.6A to J: (A) Lateral radiograph of a patient with OPLL. (B) Axial CT demonstrating severe stenosis due to OPLL. (C) Sagittal MRI. (D and E) Flexion/extension radiographs demonstrating slight subluxation at C4/5. (F) Postoperative radiographs following laminectomy and posterior instrumentation. (G and H) Postoperative MRI following laminectomy and posterior instrumentation demonstrating increased space available for the spinal cord. (I and J) Postoperative flexion/extension radiographs.

cervical corpectomy and fusion. Hasegawa et al.⁷⁸ compared pedicle screw fixation with laminoplasty and reported higher operative times and more blood loss in the pedicle screw group. They concluded that the risk of vertebral artery or nerve injury was not justified with pedicular fixation in patients with standard OPLL. There is also description of spinous process wiring techniques for fusion reported by Epstein⁷⁹ that had 100% fusion rate and low complications. Obviously, this technique is difficult to perform following multilevel laminectomy.

Laminoplasty is a technique that has been around for many years and used for posterior decompression of the spinal canal in patients with cervical OPLL. There have been multiple techniques described. The benefits of this procedure, compared with laminectomy, are reduced risk of postoperative kyphotic deformity and a decrease in scar tissue around the cord, which can be associated with neurological deterioration.⁸⁰⁻⁸² There are, however, some limitations of laminoplasty including potential for the door closing,⁵³ axial neck pain, risk of OPLL progression, limited access to the hinged side in open-door laminoplasty, and

decreased effectiveness in cases with significant kyphotic deformity and large OPLL. The open-door laminoplasty technique has been modified to prevent closure by placing a spacer or bone graft at the site,⁸³ or by using a miniplate system to secure the opening.⁸⁴ There has also been report of rapid, unexpected OPLL progression with laminoplasty⁸⁵; therefore, adequate decompression proximally, distally, and transversely must be accomplished. The adequacy of spinal cord decompression after double-door laminoplasty was evaluated by Seichi et al.⁸⁶ using intraoperative ultrasonography. They found that an OPLL maximal thickness >7.2 mm was a cutoff value for insufficient decompression, but also found that neurological outcomes at 2 years did not correlate with adequacy of decompression.

The expansion ratio of the spinal canal and the increased inclination angle of the lamina two techniques was compared by Hirabayashi et al.⁸⁷ Open-door laminoplasty produced a significantly larger expansion ratio at C6 than double-door laminoplasty and the increase of inclination angle of the lamina was significantly larger in the double-door technique. They concluded that the surgical indications

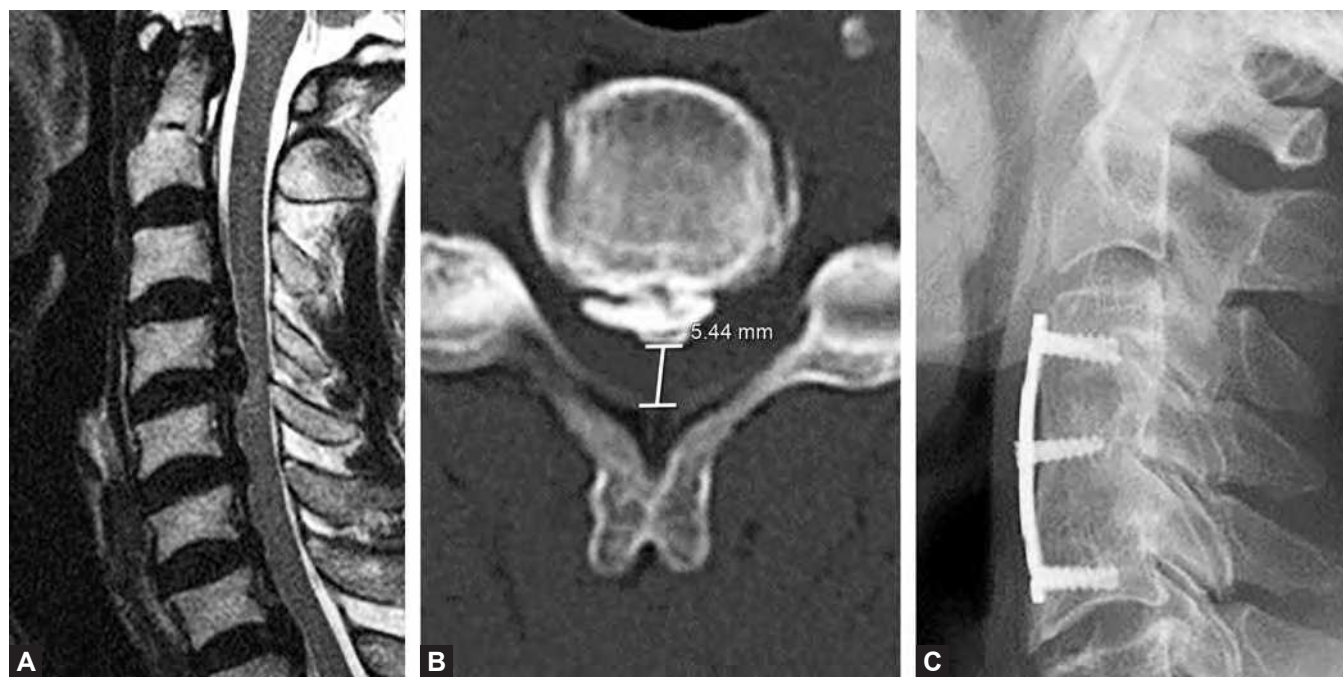
for open-door laminoplasty included cervical spondylotic myelopathy (CSM) combined with hemilateral radiculopathy, large prominence of OPLL, and patients with a tiny spinous process who cannot undergo double door laminoplasty. The indications for double-door laminoplasty include CSM, small and slight prominence of OPLL, CSM combined with bilateral radiculopathy, and cervical canal stenosis combined with instability necessitating posterior spinal instrumentation surgery.

Long-term results with at least 5 years of follow-up of open-door laminoplasty showed recovery rates between 47.9% and 63.1%.⁸⁸⁻⁹² Expansive laminoplasty was shown to be a benefit even in patients with severe myelopathy.⁹³ All patients with symptoms <3 years, and 50% of patients with symptoms present from 3 to 6 years, improved after surgery. There are several factors that influence surgical outcomes following laminoplasty. Worse outcomes are associated with duration of myelopathy,^{89,93,94} severity of myelopathy,⁹⁰⁻⁹² age,⁸⁹⁻⁹¹ preoperative kyphosis,⁸⁸ occupying ratio >60%,⁹¹ and hill-shaped ossification.⁹¹ Neurological function was found to be significantly improved after surgery, maintained for 5 years, and slightly decreased after 5 years.^{88,95} Ogawa et al.⁹⁵ also found that the degree of deterioration correlated with cervical range of motion. This motion is decreased by approximately

32%^{96,97} after laminoplasty and plateaus by 18 months after surgery.⁹⁶ C5 nerve root palsy after laminoplasty or laminectomy has been a concern. Sakaura et al.⁹⁸ found the incidence of postoperative C5 palsy to be 4.6%. It is believed to be due to a tethering effect versus local ischemia of the C5 nerve root after posterior drift of the cervical spinal cord after decompression.^{99,100} Selective C5 foraminotomies can be performed in an effort to relieve tension on the C5 nerve root; however, patients with C5 palsy generally have a good prognosis for functional recovery.¹⁰¹

Anterior Approaches

Anterior approaches are all variations of corpectomies or discectomies with or without fusion. Procedures include ACDF, anterior cervical corpectomy and fusion (ACCF),¹⁰² open-window corpectomy, oblique corpectomy (the ventral half of the body is preserved), skip corpectomy, and anterior corpectomy with floating technique. Neurologic improvement rates for the various techniques range from 51% to 71.7%. Even in poor-grade patients (Nurick grades 4 and 5), Rajshekar and Kumar¹⁰³ showed that corpectomies led to neurologic improvement in 76% of patients. Anterior cervical discectomy and fusion (Figs. 44.7A to C) is a very useful procedure in the treatment of OPLL. Koyanagi et al.⁶⁸ reported a high incidence of associated disc



Figs. 44.7A to C: T2 magnetic resonance imaging, computerized tomography scan, and postoperative plain radiograph (A to C) depicting segmental ossification of the posterior longitudinal ligament treated with anterior corpectomy and fusion.

herniation in patients with cervical OPLL, and found that disc herniation was present at the level of maximal compression in 60% of patients. This is the procedure of choice for circumscribed-type OPLL; however, it is not indicated in multilevel, continuous-type OPLL. The recovery rate with ACDF ranges from 51% to 63.2%.^{104,105} There has also been report on endoscopic ACDF by Tan et al.¹⁰⁶ with good results, but it can only be used at C4-C5 and C5-C6 levels.

Long-term follow-up (mean 14.7 years) of anterior interbody fusion without decompression was investigated by Onari et al.¹⁰⁷ in patients with cervical OPLL. Twenty four of 30 patients improved after surgery and the procedure was more effective for patients with the segmental and circumscribed type. This study indicated that a dynamic factor is an important contributor to myelopathy in patients with cervical OPLL.

The open-window corpectomy technique has been described and creates a more stable construct with three-point fixation and better load sharing between implants and healthy vertebrae. The open-window corpectomy technique is designed to remove a minimal amount of bone and achieve satisfactory decompression. With the use of a high-speed drill under a surgical microscope, only the dorsal surface of the corpus is removed after appropriate microdissectomies. This leaves the anterior and the lateral portions of the vertebral corpus intact. The technique was used by Ozer et al.¹⁰⁸ and reported satisfactory outcomes.

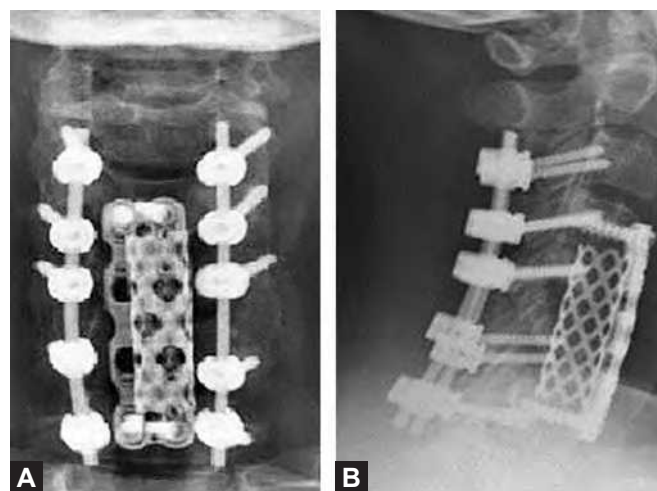
Oblique corpectomy is a technique that preserves the ventral half of the vertebral body so fusion and stabilization is not required. Two case series, one by Goel and Pareikh¹⁰⁹ and the other by Chacko and Daniel,¹¹⁰ both used this technique with clinical success.

The skip corpectomy technique involves nonadjacent level corpectomies with preservation of the intermediate vertebral body. Dalbayrak et al.¹¹¹ performed this technique in 29 patients with multilevel CSM and OPLL. The mean JOA score improved from 13.44 to 16.16 after surgery. There was only one complication with C7 screw pullout; overall they found that retention of the intermediate vertebral body fixation strengthened the construct. The floating method with anterior corpectomy and fusion described by Yamaura et al.¹¹² involves floating the OPLL segment after the corpectomy. This procedure causes decompression of the spinal cord and restores its function by enlarging the neural canal with anterior migration of the ossified ligament. The procedure minimizes the extent of surgical invasions and avoids damage to the neural tissue, because it does not require the removal of the OPLL. It also may

prevent postoperative regrowth of the ossification. Sakai et al.¹¹³ performed a 5-year prospective study comparing the anterior floating method to laminoplasty. They showed that the floating method has acceptable outcomes and is suitable for patients with massive OPLL and preoperative kyphosis, although there is a higher rate of surgical complications with the floating method compared to laminoplasty.

Surgical Decision Making for Cervical OPLL

There is no consensus for optimal surgical technique for cervical OPLL. Numerous factors should be taken into consideration on a case-by-case basis to decide the best approach: number of levels involved, amount of kyphosis of the cervical spine, whether the OPLL lesion occupies >60% of the spinal canal, and type of OPLL. In order for a posterior procedure to be effective, there must be at least some lordosis to allow the spinal cord to drift posteriorly away from the OPLL lesion. Also, large OPLL (> 60% of spinal canal) has better outcomes with decompression anteriorly.¹¹³ Continuous-type may be better dealt with using a posterior approach, whereas isolated segmental- or circumscribed type may be better handled with an anterior approach. Large continuous lesions may be better served with multilevel anterior corpectomy and posterior spinal fusion for further stabilization (Figs. 44.8A and B). The



Figs. 44.8A and B: Postoperative radiographs of an anterior corpectomy with fusion and posterior fusion for a large, continuous ossification of the posterior longitudinal ligament. Shows anterior and posterior instrumentation C3-C7.

advantages and disadvantages of surgical procedures for cervical OPLL are displayed in Table 44.2.

SURGICAL TREATMENT OF THORACIC OPLL

The outcomes after surgical treatment of thoracic OPLL are poorer than the results after cervical OPLL. There are several reasons for the limited effectiveness of decompression in the thoracic spine.^{114,115} The first factor is the natural kyphosis of the thoracic spine that restricts the backward shift of the spinal cord away from the OPLL with posterior decompression. The second factor is that the thoracic spinal cord is relatively avascular and more vulnerable to ischemic injury during surgical manipulation. Lastly, the ribcage restricts surgical approaches to the spine.

Surgical options for thoracic OPLL include posterior laminectomy or laminoplasty, posterior decompression and fusion, anterior transthoracic decompression, circumspinal decompression posteriorly with costotransversectomy, and two-stage anterior and posterior decompression.¹¹⁶ The simplest method is posterior decompressive laminectomy alone; however, this technique disrupts the posterior tension band of the thoracic spine and may lead to instability and neurologic deterioration. There have been reports of laminectomy in patients with thoracic OPLL that suffered postoperative neurologic deterioration.^{117,118} These two patients underwent reoperation with instrumented fusion and both gradually improved neurologically. Nakanishi et al.¹¹⁹ redemonstrated the importance of fusion after laminectomy after seeing a decrease in evoked potentials after laminectomy with subsequent return of amplitude after posterior instrumented fusion. Matsumoto et al.¹²⁰ also recommended posterior instrumented fusion after looking at factors related to outcomes after thoracic OPLL surgery. The above studies emphasize the importance of a dynamic factor with progression of kyphosis as the cause of neurological deterioration after laminectomy alone. There are two descriptions of thoracic OPLL: beak type and flat type. Flat type is analogous to low profile continuous type in the cervical spine. There are no sharp or large protrusions. Beak type has more of a large, sharp protrusion on sagittal view that resembles the beak of a bird. Beak type has a higher risk of neurological deterioration after posterior decompression.¹²¹

Thoracic laminoplasty was evaluated by Komagata et al.¹²² and Matsumoto et al.¹²⁰ Both studies showed the effectiveness of laminoplasty; however, it is safer to only use

it at the nonkyphotic upper thoracic spine (T1-T4) as there were two cases of transient leg paralysis in the mid-to-lower thoracic spine.

Posterior decompression with fusion generally has a lower complication rate compared with posterior decompression alone and anterior approaches. Yamazaki et al.¹²³ performed one of three approaches on patients with thoracic OPLL: posterior decompression alone, posterior decompression and fusion, and anterior approach with extirpation. Decompression alone had the highest complication rate followed by anterior extirpation. The fusion group had no cases of postoperative paralysis or late neurological deterioration. Due to the thoracic kyphosis, the ability of decompression and fusion to effectively improve neurologic function has been questioned. Yamazaki et al.¹²⁴ followed patients for over 4 years after posterior decompression and in situ fusion. There was only a 58.1% recovery rate and the median time to maximal recovery was 9 months.

Posterior decompression with kyphosis correction has also been studied with a recovery rate ranging from 56% to 68%.^{125,126} Zhang et al.¹²⁶ performed posterior decompression and fusion with 5°–15° of kyphosis correction. Postoperative MRI showed backward shift of the spinal cord and complete decompression in all cases.

Tokuhashi et al.¹²⁷ determined that the critical ossification-kyphosis angle that affects outcome in patients who underwent posterior thoracic decompression is 23°. All patients with an angle >23° had no echo-free space detected by intraoperative ultrasound, whereas all patients with <23° had echo-free space.

The anterior approach alone for thoracic OPLL is technically demanding and has poor surgical results, especially in patients who already have severe spinal cord compression. Min et al.¹²⁸ reported high complication rates with anterior decompression in 19 patients with thoracic OPLL. Two patients developed neurological deterioration and six patients developed CSF leakage.

The circumspinal decompression from a posterior only approach has the benefit of anterior and posterior decompression and stabilization with only one surgical approach. Yang et al.¹²⁹ reported satisfactory outcomes using this technique for T10-T11 OPLL. Takahata et al.¹¹⁶ reported on a series of 30 patients with this technique followed for 8 years. The JOA score improved in 24 patients; however, there were significant complications, including 40% with dural tears, 10% with deep infections, and 33%

Table 44.3: Summary of advantages and disadvantages for thoracic OPLL surgery.

<i>Surgical procedure</i>	<i>Advantages</i>	<i>Disadvantages</i>
Post decompression	Simple, less operating time and blood loss	High risk for Postop paralysis and late neurological deterioration
Post decompression w/fusion	Less operating time and blood loss compared w/Ant or combined approach, low risk of Postop paralysis	Persistent Ant impingement of spinal cord by OPLL
Ant decompression through Ant approach	Direct removal of OPLL	High risk for Postop paralysis and CSF leakage, technically demanding, more operating time and blood loss
Circumspinal decompression through Post approach	Immediate Ant and Post decompression and stabilization w/only 1 operation	Technically demanding, more operating time and blood loss
2-stage Post, Ant decompression	Complete Ant and Post decompression	Technically demanding, more op time and blood loss

(OPLL: Ossification of the posterior longitudinal ligament, Ant: Anterior; Post: Posterior; Postop: Postoperative).

Source: Saetia K. Cho D. Lee S. et al. Ossification of the posterior longitudinal ligament: a review. Neurosurg Focus. 2011;30(3):E1.

with postoperative neurological deterioration. Patients with decompression of five or more levels had worse outcomes. Other reports by Hioki et al.¹³⁰ and Kawahara et al.¹³¹ described circumspinal decompressive techniques, which generally had improvements with surgery; however, both had significant complications including dural tears and neurological deterioration.

Surgical Decision Making for Thoracic OPLL

The surgical outcomes of patients with thoracic myelopathy are correlated with preoperative duration of symptoms and the degree of myelopathy. Patients with shorter duration of symptoms and milder myelopathy experienced the best surgical outcomes.²³ There is still no consensus or definitive guidelines for the surgical treatment of thoracic OPLL. Numerous factors should be taken into consideration when deciding to operate on symptomatic thoracic OPLL: number of levels and type of OPLL, amount of cord compression, and the experience of the surgeon. Generally, most studies indicate that posterior decompression and fusion with or without mild kyphosis correction will provide adequate surgical outcomes with the least risk of complications. However, with very severe compression, there is a role for posterior decompression and fusion with subsequent anterior decompression. The advantages and disadvantages of surgical procedures for thoracic OPLL are summarized in Table 44.3.

SURGICAL MANAGEMENT OF LUMBAR OPLL

Symptomatic lumbar OPLL is much rarer but does exist and usually is located in the upper lumbar spine where the posterior longitudinal ligament is much broader. Patients may present with cauda equina syndrome and most are approached posteriorly with decompression. Tamura et al.¹³² described two cases of lumbar OPLL: one treated with an anterior approach and the other with an anteroposterior approach. They recommended combined anterior-posterior surgery in patients with OPLL occupying a large part of the spinal canal.

SURGICAL COMPLICATIONS

Although most complications were discussed in the above sections, Li et al.¹³³ performed a systematic review of complications in cervical OPLL surgery. The authors found that the main complications to be cerebrospinal fluid leakage (CSF), neurologic deficit including motor weakness or palsy, such as C5 palsy and sensory disturbances, axial neck pain, implant complications, nonunion, hoarseness, dysphagia, dyspnea, and hematoma. Anterior approach surgery has a higher incidence of CSF leak, implant complications, and hoarseness, dysphagia, and dyspnea. Posterior approach is most commonly associated with axial neck pain and C5 palsy. Other neurologic deficits were seen with both approaches and were found to be the most common complication in cervical OPLL surgery. Most deficits completely resolved spontaneously but recovery time varied from 1 week to 2 years.

CONCLUSION

Ossification of the posterior longitudinal ligament is a disease predominantly found in people of Asian descent but is found to a lesser extent across the globe. The exact etiology is not fully elucidated, but there is a strong genetic component with multiple genes currently being studied as major contributors to the disease. There is also believed to be a dynamic, mechanical component that leads to the myelopathy seen in the disease. The natural history shows that people that present without myelopathy are unlikely to progress and prophylactic surgery is not needed. Patients with myelopathy generally will require surgical intervention to prevent progression of symptoms. There are four types of OPLL, and they all can be evaluated with various diagnostic studies including plain radiography, CT scan, and MRI. Surgical treatment of OPLL should be considered on a case-by-case basis. There is no consensus or standard treatment for OPLL, but general guidelines can help direct the approach. Patients with kyphosis, lesions occupying >60% of the canal, and segmental-type OPLL have better outcomes with an anterior approach. Smaller, continuous lesions with no kyphosis are better served with a posterior approach. Patients with thoracic OPLL have poorer outcomes than cervical OPLL in general, but adequate recovery can be obtained with posterior decompression and fusion with possible anterior decompression. Complications can occur with all approaches, but overall have acceptable rates and generally favorable prognosis.

KEY POINTS

- Ossification of the posterior longitudinal ligament predominantly affects people of Asian descent, but can be found around the globe.
- The etiology of OPLL is not fully elucidated; however, there is a strong genetic and mechanical component leading to the formation and progression of the disease.
- The natural history shows that patients that present without myelopathy are unlikely to progress; however, patients with progressive myelopathy will need surgical intervention to halt the progression.
- There are four types of OPLL: continuous, segmental, mixed, and circumscribed. They are best evaluated with CT scan for the bony lesion and MRI for the impact on the spinal cord.

- There are multiple surgical approaches for OPLL with no general consensus as to the best approach. Anterior approaches are most favorable for lesions >60% of the spinal canal diameter, segmental type, and when there is kyphosis present. Posterior approaches are better suited for continuous-type, smaller lesions with no kyphotic deformity.
- Complications occur with all approaches. Dural tears, hardware issues, and dysphagia are most common with anterior surgery, and axial neck pain and nerve palsies (C5) are more common with posterior surgery.

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- A multicenter retrospective cohort was performed. Patients with OPLL were followed for an average of 10.6 years. They found that patients with > 60% spinal canal stenosis, those with more cervical range of motion, and lateral deviated OPLL developed myelopathy more frequently than those patients without these findings.
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- 14-year follow-up of 80 patients with OPLL treated with the original open-door laminoplasty had improvement with surgery up to 3 year with slight decline after 5 year. There was late neurologic deterioration and kyphosis in multiple patients that are challenging problems.
- Sakai K, Okawa A, Takahashi M, et al. Five-year follow-up evaluation of surgical treatment for cervical myelopathy caused by ossification of the posterior longitudinal ligament: a prospective comparative study of anterior decompression and fusion with floating method versus laminoplasty. *Spine (Phila Pa 1976)*. 2012;37(5):367-76.
- Prospective study comparing anterior floating method decompression with laminoplasty. They found anterior surgery with this technique is acceptable for cases with large OPLL and kyphosis but leads to higher surgery-related complications than laminoplasty.
- Li H, Dai LY. A systematic review of complications in cervical spine surgery for ossification of the posterior longitudinal ligament. *Spine J*. 2011;11(11):1049-57. This is a review of the literature for complications in surgical treatment of cervical OPLL. Anterior surgery was associated with CSF leaks, implant complications, and dysphagia whereas posterior surgery was associated with axial neck pain and C5 palsy. Overall complication rate was 21.8%.

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Occipitocervical and Atlantoaxial Fusion

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Snapshot

- » Surgical Approach: Anatomic and Technical Considerations
- » Indications for Surgery
- » Atlantoaxial Fixation Options
- » Transoral Atlantoaxial Reduction Plate
- » Occipitocervical Fixation Considerations and Options

INTRODUCTION

Methods for fusing the occipitocervical and atlantoaxial spine have evolved significantly with changes in instrumentation techniques. Historically, C1-C2 fusion techniques involved the use of corticocancellous autografts or allografts and wires, as per the Gallie, Brooks-Jenkins, and the Sonntag techniques. Methods for occipital fixation involved expansions on the use of the corticocancellous bone grafts to involve the occiput, using burr holes in the occiput to thread wires through for fixation. This was a technique first described and used by Drummond and Dormans in 1995 and subsequently modified by the use of structural rib allograft described in 2001.^{1,2} However, with the modernization of instrumentation, fixation techniques evolved away from wiring, to plate and screw fixation, to what is now predominantly a skull plate attached by rods to screws in the spine.

The transition from a predominant wire-based fixation to screw and rod fixation started with Magerl and Seeman in 1987, where a posterior transarticular screw combined with posterior wiring was used to provide more rigid fixation from traditional techniques. Percutaneous techniques have been described by Dickman et al. and McGuire et al. in 1995.³⁻⁵ However, biomechanical studies started to provide objective evidence of superior fixation provided by screw fixation over wires, setting the stage for the

transition to all screw/rod constructs.⁶ Goel, and later, Harms, described the technique for C1-C2 arthrodesis with an all screw construct.^{7,8} Anterior C1-C2 transarticular screws, described by Lu, is yet another method of C1-C2 fixation, although not as popular as the other methods.⁹

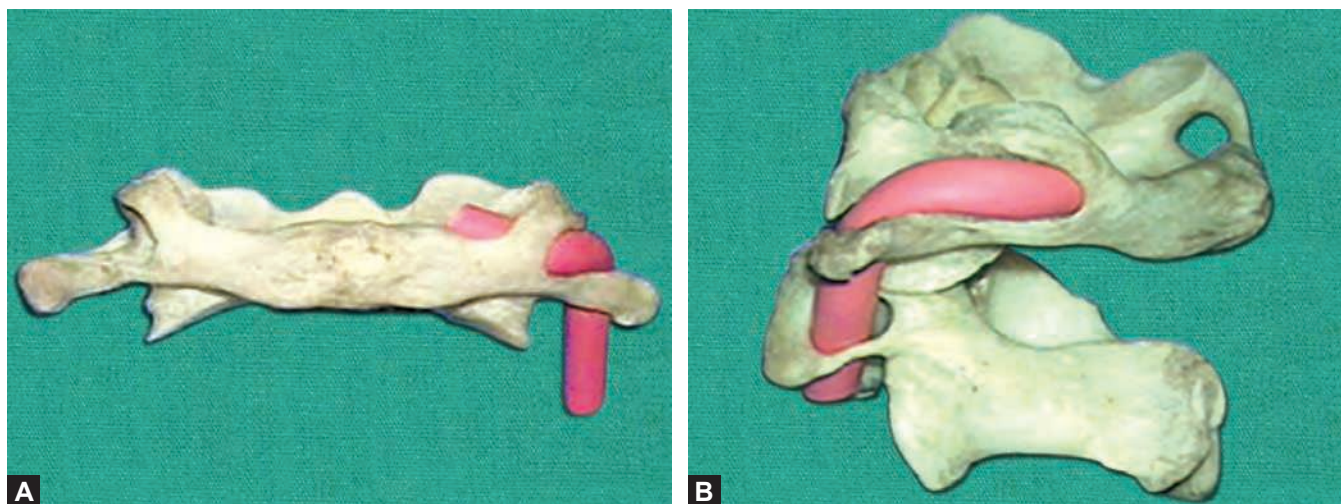
This chapter reviews modern techniques used in O-C and C1-C2 fusions with a bias toward those techniques utilized by the senior author K.D.R. A specific focus is placed on the technical aspects of the operative techniques utilized.

SURGICAL APPROACH: ANATOMIC AND TECHNICAL CONSIDERATIONS

The surgical approach for screw and rod fixation involves a more thorough knowledge of the normal anatomy as well as its variations or anomalies and often, a wider surgical dissection when compared to historical techniques such as the Gallie fusion. Specific anatomic considerations include the vertebral arteries, the C2 dorsal root ganglion and greater occipital nerve, the C1-C2 venous plexus posteriorly and the internal carotid artery, hypoglossal, glossopharyngeal and superior laryngeal nerve anteriorly.

Posterior Upper Cervical

The exposure of the upper cervical spine involves an incision that extends from the base of the occiput to the



Figs. 45.1A and B: (A) Coronal view of the C1 vertebrae and its relationship to the vertebral artery. (B) Notice on this sagittal view, the position of the vertebral artery, ventral to the C1 lamina.

spinous process of C2. When the fusion is limited to C2 and above, the insertion of the fibers of the semispinalis cervicis on the dorsolateral and caudal aspect of the C2 spinous process must be preserved because this muscle is the main extensor of cervical spine and its detachment may cause neck pain, kyphosis, and limitation of motion. This is especially important for C1-C2 fusions that do not involve fixation of more distal levels.

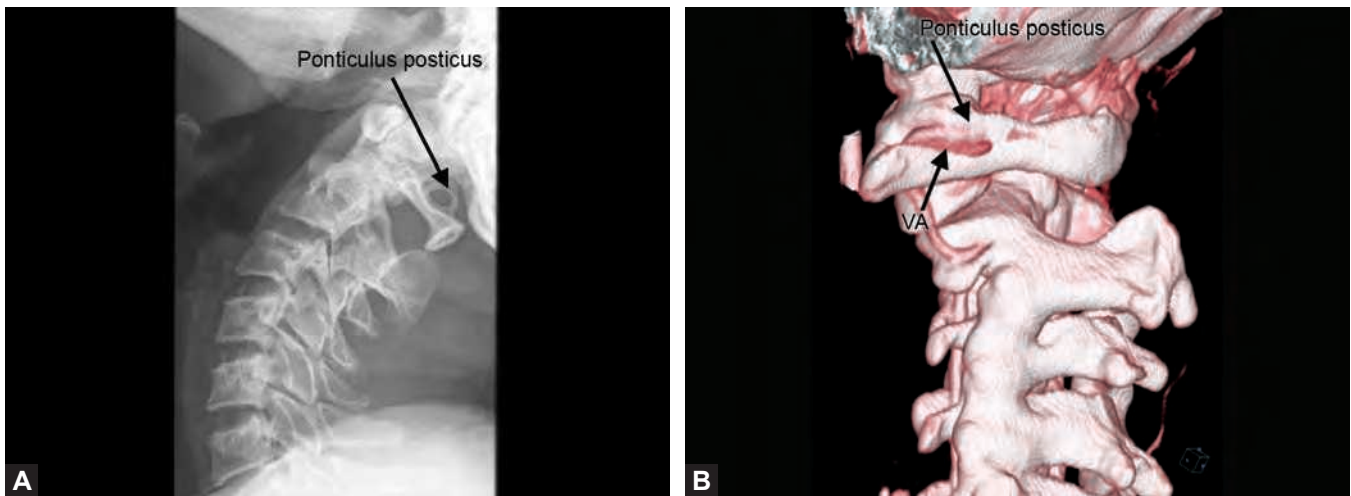
The typical course of the vertebral artery after it comes through the transverse foramen at C1 is to course medially and dorsally. This places the artery on the cranial edge of the lateral aspect of the C1 lamina before it enters the foramen magnum. Exposure of the C1 lamina farther than 1.5–2 cm from midline places the vertebral artery at risk for injury. Just caudal to the lamina, however, we routinely dissect 2–3 cm lateral to the midline, in order to expose the ideal starting point for a C1 lateral mass or posterior arch screw. We use a broad Cobb elevator to very gently dissect the muscles off of the posterior arch of C1 and have found this to be a safe technique, as the artery usually lies ventral to the arch (Figs. 45.1A and B). Usually, the superior aspect of the artery is not bordered by bone, while the inferior edge sits on the C1 lamina; however, sometimes, the artery is completely encased within bone superiorly, and this rostral osseous edge is called the *ponticulus posticus*¹⁰ (Figs. 45.2A and B). This can easily be identified on a lateral radiograph. Magnetic resonance imaging (MRI) or computerized tomography (CT) angiogram can be useful to rule out vertebral artery aberrancies such as high riding vertebral artery and vertebral artery anomalies such as fenestration and persistent first intersegmental artery. At the very least, a preoperative CT is absolutely mandatory to check for a

high riding or aberrant vertebral artery course, as well as bony dimensions that may preclude the use of transarticular, pedicle, or pars screws.

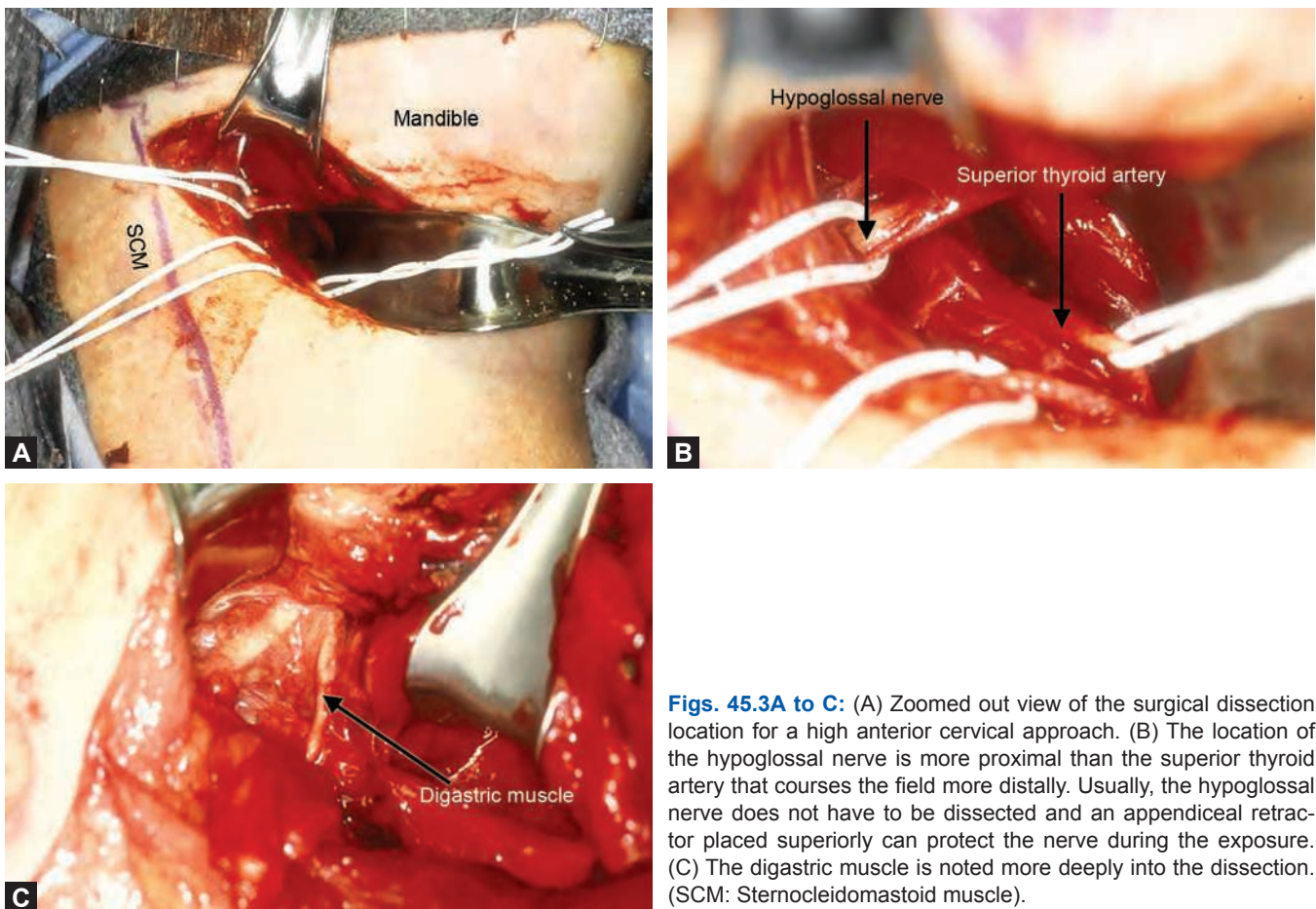
During deep dissection of C1 and C2 near the C1-C2 facet joint, a slow and careful subperiosteal dissection with the use of a Penfield 4 retractor may be helpful to avoid injury to the venous plexus and the C2 nerve root and its dorsal ganglion. Excess bleeding is controlled with a combination of bipolar electrocautery, liquefied collagen or collagen sponges with thrombin, surgicel, and pressure with patties.

Anterior Upper Cervical

The anterior approach to the upper cervical spine may be performed through a Smith–Robinson approach. One needs to dissect posterior and superior to the angle of the jaw and the submandibular gland. Bohlman and McAfee described this approach for exposing the upper cervical spine.¹¹ While interesting, we find this description to be overly complex. By using careful, mostly blunt dissection with scissors, under the microscope, and not cutting any nerves crossing the field, we have exposed countless cases up to C2 and only bother to look for the nerves that cross the field out of academic interest. Some important neurologic structures that are typically not seen are the superior laryngeal nerve, which usually crosses the field at about the C3–C4 region. It usually runs with the superior thyroid artery and vein. The glossopharyngeal nerve is found more cranial and crosses deep to the external carotid artery (Figs. 45.3A to C). It is close to the digastric muscle and is typically much thicker than the superior laryngeal nerve.



Figs. 45.2A and B: (A) A lateral radiograph demonstrating a ponticulus posticus with the (B) corresponding computerized tomography reconstruction; notice the relationship of where the vertebral artery (VA) courses in relation to the C1 lamina and the ponticulus posticus.



Figs. 45.3A to C: (A) Zoomed out view of the surgical dissection location for a high anterior cervical approach. (B) The location of the hypoglossal nerve is more proximal than the superior thyroid artery that courses the field more distally. Usually, the hypoglossal nerve does not have to be dissected and an appendiceal retractor placed superiorly can protect the nerve during the exposure. (C) The digastric muscle is noted more deeply into the dissection. (SCM: Sternocleidomastoid muscle).

The hypoglossal nerve is usually more superficial as it crosses over the external carotid artery before diving deep to the stylohyoid and mylohyoid muscles. Careful blunt

dissection will protect the structures from iatrogenic injury. Small crossing vessels can be clamped with a hemostat and then coagulated with bipolar cautery to

physically and thermally occlude the lumen, obviating the need for clips or suture ligation.

■ INDICATIONS FOR SURGERY

There are a variety of indications for surgical intervention at the occipitocervical and atlantoaxial joints. Generally speaking, surgery is indicated if a condition causes severe instability, severe local pain including that caused by arthritis or destruction of the facet joints, or neurologic compromise including myelopathy as well as C2 root compression causing intractable occipital neuralgia. These conditions can be broken into broad categories of degenerative, developmental, congenital, inflammatory, infectious, traumatic, and neoplastic etiologies. A discussion into the specifics of the cause for instability, pain, or neurologic compromise from these conditions is beyond the scope of this chapter but should nevertheless be understood and recognized by spine surgeons.

■ ATLANTOAXIAL FIXATION OPTIONS

The authors' preferred technique for C1-C2 arthrodesis is the C1 lateral mass screw and C2 pedicle screw fixation. The advantages of this technique over others such as transarticular fixation are many. First, the fixation of C1 and C2 individually allows for reduction of any subluxations after instrumentation during rod assembly.¹² This is in contrast to transarticular screws where one has to reduce first and then instrument while holding the reduction. Second, placement of pedicle screws at C2 allows for less of a dissection than the C2 pars screw, which has a more distal and medial starting point. Lastly, the placement of C1 lateral mass screws and C2 pedicle screws does not need fluoroscopic guidance as opposed to the placement of transarticular screws.¹³ As stated above, a preoperative CT is necessary to determine if the C2 pedicles are large enough to accept a screw. A high riding or medial vertebral artery will preclude the possibility of a pedicle screw (Figs. 45.4A to C). In such cases, one can use a pars or a C2 laminar screw, described by Wright.¹⁴

Anterior C1-C2 Transarticular Screw Fixation

Lu et al. described the anatomic parameters for the placement of anterior C1-C2 transarticular screw fixation.⁹ They concluded that anterior transarticular screws, which uses a starting point at the concavity on the anterior cortex of

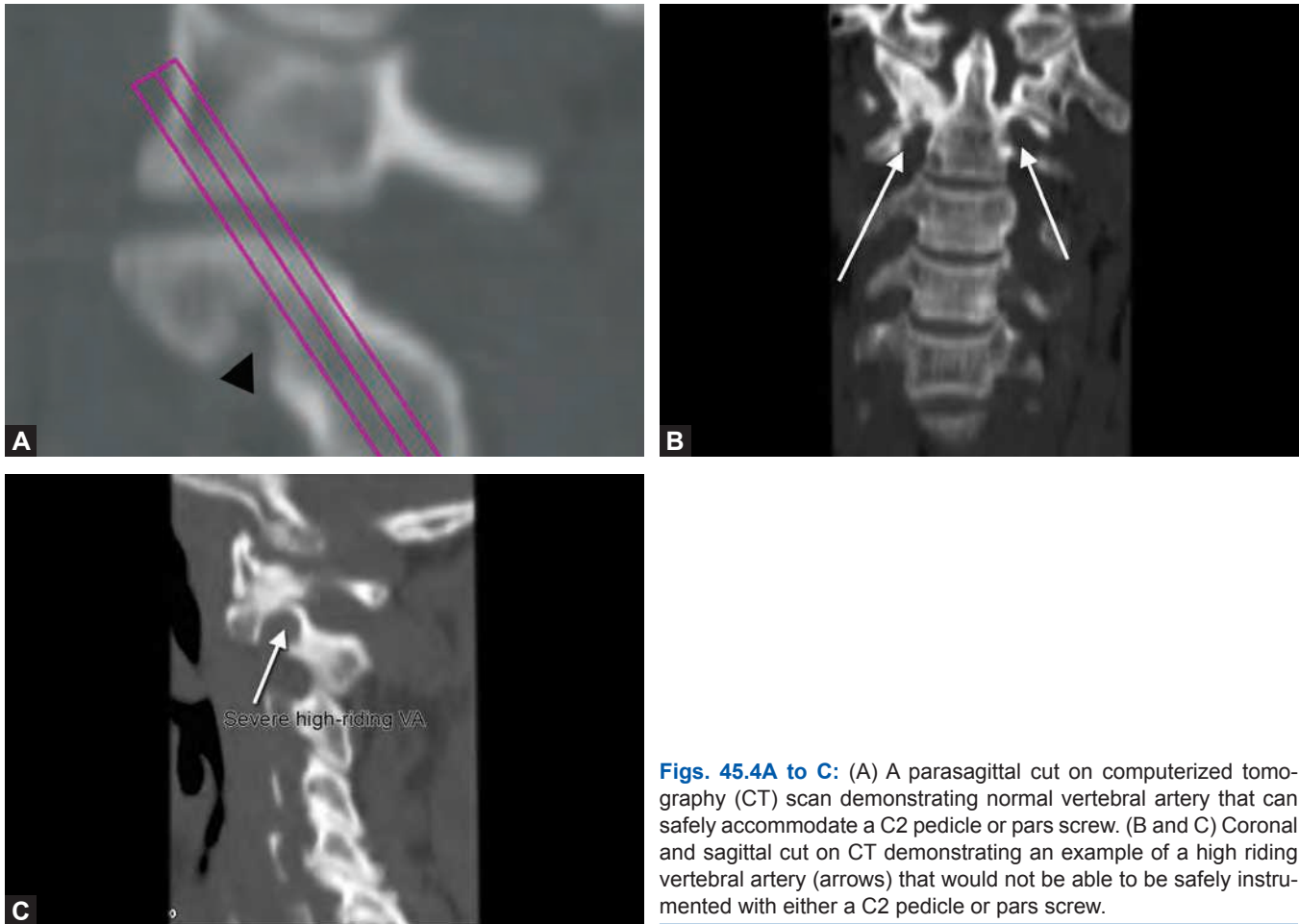
the C2 arch, should be angled 20° laterally and 20° posteriorly to be placed safely. With this method, a screw length of 15–20 mm is usually sufficient.⁹

More recently, percutaneous methods for anterior transarticular screw placement have been described.^{15,16} This technique uses a starting point at the anterior inferior endplate of the C2 vertebral body with a trajectory that is aimed 20–30° lateral and 20–28° posteriorly. With this method, a screw length of 40–50 mm can be achieved.

There are several challenges to placing anterior transarticular screws. These include the potential damage to the superior laryngeal nerve as well as problems with dysphagia that are associated with an anterior procedure. In addition, the mandible makes it difficult with even open anterior approaches to adequately decorticate and bone-graft the C1-C2 joints bilaterally. A transoral decortication and grafting may be necessary. Lastly, the trajectories of the anterior screws are directed from medial to lateral. This means that while the contralateral screw might be easier to place, screw placement for the ipsilateral side of the approach will require extensive retraction of the midline structures past midline.¹² Nonetheless, this approach is a useful adjunct to a cervical spine surgeons' armamentarium because certain circumstances make this a better option for fixation (i.e. abnormal vertebral artery course or the absence of posterior osseous structures due to prior surgery).

■ TRANSORAL ATLANTOAXIAL REDUCTION PLATE

Since being described in the literature in 2005,¹⁷ the transoral atlantoaxial reduction plate has been indicated for an irreducible atlantoaxial dislocation due to basilar invagination, Arnold-Chiari malformation, congenital odontoid dysplasia, free dens, rheumatoid arthritis, old odontoid fractures, and old C1 transverse ligament disruption.¹⁸ This technique necessitates the anatomic structure of the C1 lateral masses and C2 vertebral body to be intact. Recently, this technique was used to treat a posterior atlantoaxial dislocation.¹⁸ The authors from this report have performed over 160 cases of C1-C2 fusions utilizing this technique for anterior atlantoaxial dislocations with good clinical results (Figs. 45.5A to D). The advantage of utilizing this technique is that a reduction, decompression, fixation, and fusion can all be achieved by a one-staged operation. Traditionally, the transoral approach has been utilized for odontoid excisions without fusion.



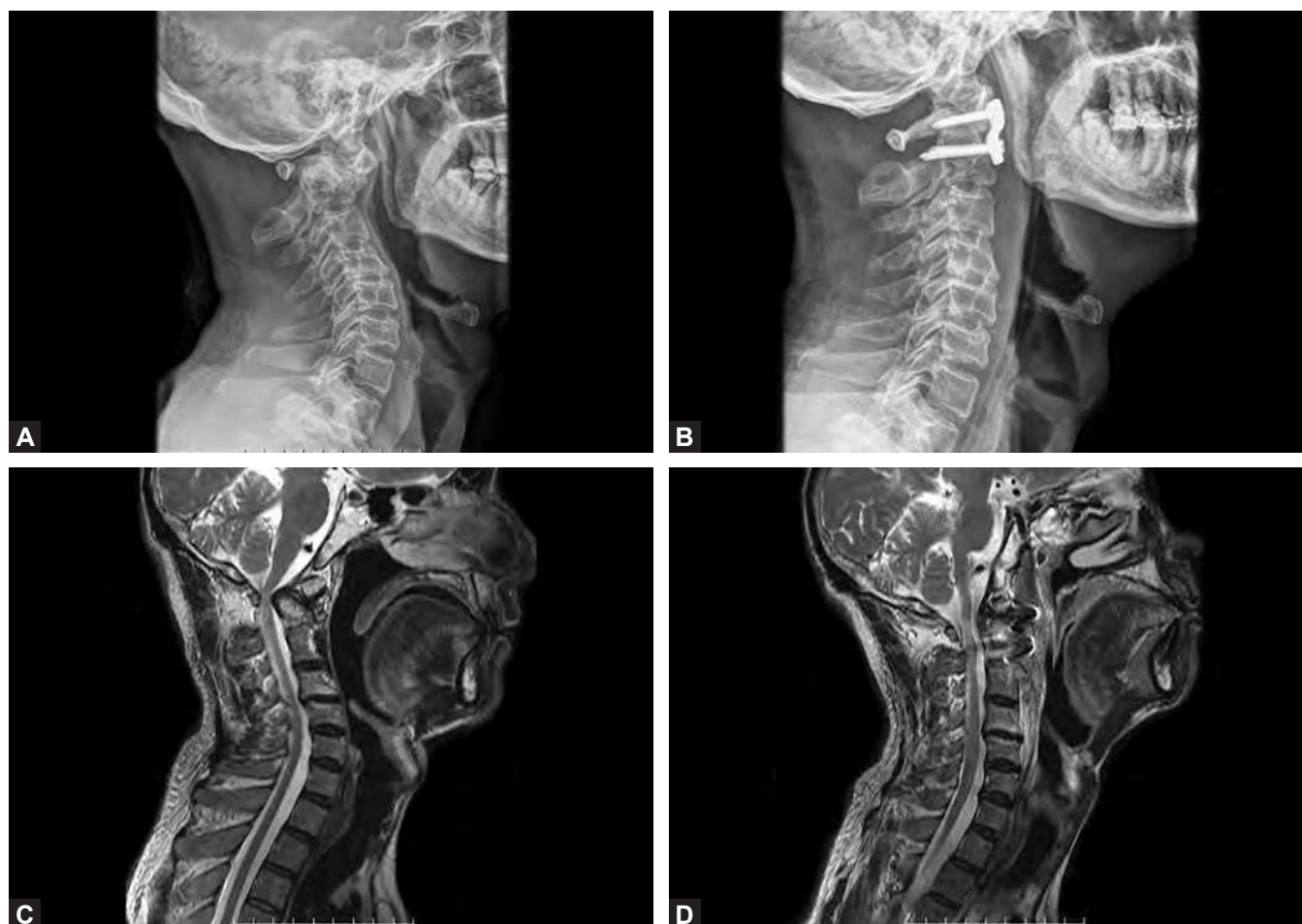
Figs. 45.4A to C: (A) A parasagittal cut on computerized tomography (CT) scan demonstrating normal vertebral artery that can safely accommodate a C2 pedicle or pars screw. (B and C) Coronal and sagittal cut on CT demonstrating an example of a high riding vertebral artery (arrows) that would not be able to be safely instrumented with either a C2 pedicle or pars screw.

Posterior Magerl Transarticular Screw

The posterior transarticular technique was first described by Magerl and Seeman and is an excellent method for providing rigid C1-C2 fixation.³ Biomechanical studies of transarticular screws have shown excellent stability except in flexion and extension.⁴ This can usually be addressed by supplementing the construct with wiring of the spinous processes of C1 and C2.

Much like any technique for instrumentation of C1 and C2, extensive preoperative imaging including plain radiographs, MRI, and CT are essential for operative planning. Sagittal and parasagittal reformatted images are critical to evaluating the location of the vertebral arteries to determine the feasibility of this technique. Sometimes, the C2 pars may be too thin or the position of the vertebral artery too medial or dorsal to allow for the use of the Magerl technique. It is estimated that up to 20% of cases exhibit anatomic limitations for using the transarticular screw, so in no way are these anatomic variations a rarity.¹⁹⁻²¹

The starting point of the C1-C2 Magerl screw is approximately 3 mm proximal to the C2-C3 facet joint line and 3 mm lateral to the medial border of the lateral mass. The trajectory in the sagittal plane of the screw will vary based on the location of the anterior tubercle of C1; however, in the coronal plane, we usually aim 0–5° medially. If there is a subluxation of C1 on C2, using any part of the C1 anterior tubercle is not recommended because the position of the C1 anterior tubercle is determined by the degree of subluxation. Instead, the screw trajectory needs to be directed as dorsally as possible in order to minimize the possibility of violating the anteriorly located C2 vertebral artery groove²²⁻²⁴ (Fig. 45.6). The amount of medial angulation depends on the location and course of the vertebral artery at the level of the C2 pars. Whenever possible, we believe that it is much better to place the screw only after reducing the C1-C2 joint first. This can be done sometimes by retracting (translating the neck posteriorly) and extending the neck. Too much extension, however, can make the screw trajectory impossible, so this should be checked prior to



Figs. 45.5A to D: (A) Lateral radiographs, (B) with corresponding magnetic resonance imaging, (C and D) status post-transoral atlantoaxial reduction plating demonstrating anatomic reduction, decompression, and restoration of the space available for the cord at C1. *Courtesy:* Dr Qingshui Yin, Department of Orthopaedics, Guangzhou General Hospital of Guangzhou Military Region, Guangzhou, Guangdong, PR, China.

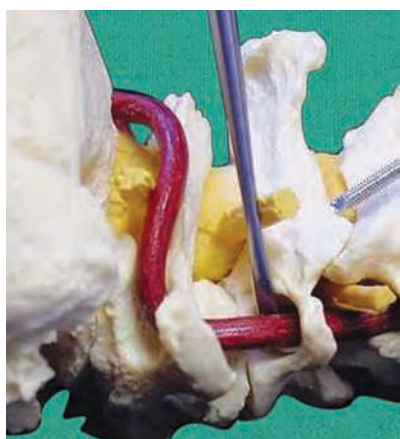


Fig. 45.6: In order to avoid possible violation of the C2 vertebral artery groove during posterior transarticular C1-C2 screw placement, the screw trajectory needs to be as dorsally directed as possible.

the prep and drape under fluoroscopy. Intraoperatively, one can place a cable under the arch of C1 and caudal to the spinous process of C2, underneath the still attached semispinalis cervicis. By tensioning the cable, the C1 ring is pulled posteriorly. If the patient has severe cord compression at the C1 level, it is sometimes possible to pull the arch posteriorly first with a Kocher or tenaculum, so as to create more space for the cord, prior to placing the cable. If this is not possible, then one should not attempt to place a cable underneath the arch of C1, as it can cause cord injury.

Under fluoroscopy, the screw tip should be directed toward the bottom half of the anterior tubercle of C1. It should stop short of the posterior cortex of the tubercle, since a longer screw will protrude into the soft tissues, placing the internal carotid artery at risk in some individuals.

The risk of vertebral artery injury with this technique is estimated to be 4.1%.¹⁴ If the artery is injured, one should place a short screw to tamponade the bleeding. With a minor injury, the artery may be able to repair itself in time. If a long screw is placed through the artery, however, it has no chance of reconstituting itself. Postoperatively, angiographic studies should be obtained to assess the injury. Most importantly, placement of a screw on the contralateral side should not be attempted, since bilateral vertebral artery injury usually results in severe neurologic deficit or death.

C1-C2 Segmental Screw Fixation

The technique for utilizing C1-C2 segmental fixation was first described by Goel with the use of screws and plates in 1994 and then by Harms and Melcher with the use of screws and rods in 2001.^{7,8} This is our preferred technique. We describe the method we use for screw fixation of the C1 lateral mass as well as C2 pedicle and review methods for salvaging fixation points in C2.

With this approach, patients are positioned prone on an Orthopedic Systems, Inc. (OSI) frame with traction placed at 15 lb through Gardner-Wells tongs. The surgical approach is that which was described in the earlier part of this text for the posterior upper cervical approach.

C1 Lateral Mass Screw

The inferior border of C1 may be delineated with electrocautery. However, care is used for the superior border, since injury to the vertebral artery can occur. A Penfield 4 or 2 is used to subperiosteally dissect the C2 ganglion and venous plexus off of the arch. Keeping the dissection completely subperiosteal is a key to avoid unnecessary bleeding from the venous sinuses.

The C2 nerve root and its dorsal root ganglion, which supplies the greater occipital nerve, is between the C1 posterior arch and C2 pars and posterior to the C1-C2 facet joint, and care is taken to use a Penfield to gently retract the nerve distally toward the C2 lamina. A large venous plexus lies just cranial, lateral and deep the C2 nerve root and care should be taken not to manipulate this area too much unless a decision is made to sacrifice the C2 nerve root, in which case aggressive bipolar cautery can be used to cauterize the venous plexus. We usually preserve the C2 nerve root and therefore use thrombin-based hemostatic agents, surgical, and mechanical pressure by way of a cottonoids to control the bleeding. Again, keeping the dissection plane strictly subperiosteal is a key to minimize

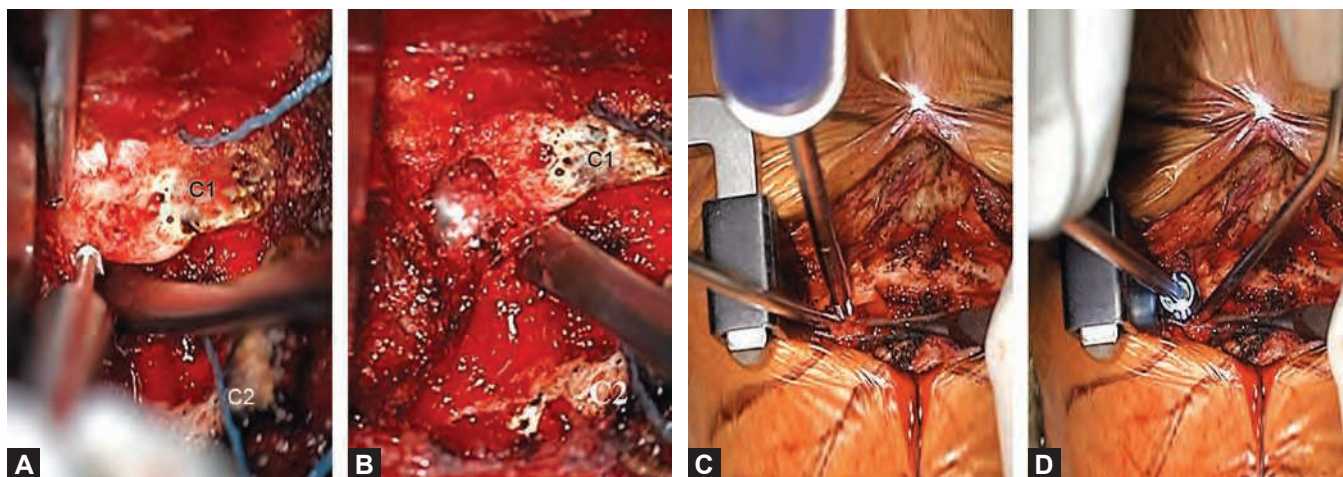
bleeding. While some have recommended routinely sacrificing the C2 nerve, a recent study found that doing so can result in disabling pain in some patients.^{25,26}

Prior to instrumentation of the C1 lateral mass, the C1-C2 articulation is decorticated with the use of a burr, while the C2 nerve root is retracted cranially, and fresh frozen allograft bone is placed along with the bone dust from the decorticated joint (see Figs. 45.5A to D). When decorticating, be aware of how close the artery is to the subchondral bone at C2 by examining the CT scan. Screw placement can now commence. Whenever possible, we utilize a C1 arch screw, as this requires less of a soft tissue dissection than a lateral mass screw.²⁶ In addition, the screw has purchase in more bone with this technique. If a lateral mass screw is necessary, we first use a Penfield 4 to identify the medial and lateral borders of the C1 lateral mass. Midway between the medial and lateral borders is the starting point for our screw.

We then notch the inferior aspect of the C1 posterior arch with a burr to create a space into which the screw will be recessed¹³ (Figs. 45.7A to D). This recess allows a more caudally directed screw trajectory because the overhang of the C1 posterior arch is eliminated. Another advantage of the notch recess is that the tulip of the screw head can also sit more cranially when the screw is inserted so that the screw heads are not too crowded after placement. Nevertheless, this step is only performed, if and only if the corresponding sagittal cuts on the CT scan as well as the MRI show that the vertebral artery would not be compromised with such a maneuver. If there is a risk for vertebral artery injury, we usually dissect the artery off of the cranial aspect of C1 and protect it with a cottonoid prior to forming the recess.¹³

The Penfield retractor then moves distally to protect the C2 nerve root. A cottonoid can be used to cushion the nerve root, so direct pressure from the Penfield is not applied to the nerve root. A drill is then placed into the recess that was burred until a bony endpoint is reached. We aim the C1 lateral mass screw 0–5° medially.^{13,27} Care is taken not to aim too cranially, since this can result in screw threads violating the O-C1 articulation. By aiming the screw as close as possible toward the C1-C2 joint without violating it, one can avoid this complication.

A radiographic and anatomic analysis on the optimal screw trajectory to prevent this occurrence concluded that a trajectory below the 40% mark of the anterior arch of the atlas on a radiograph was the safe zone for C1 lateral mass screw placement.²⁷ There are certain anatomic



Figs. 45.7A to D: (A) Recessing the inferior margin of the C2 lamina allows for a more caudally directed trajectory of the C2 lateral mass screw in order to avoid violation of the occipitocervical joint. (B) This can be safely performed by confirming the position of the vertebral artery. (C) Once tapped and the screw is placed (D), you can see that the tulip of the screw head is located more cranially which also prevents impingement of the C2 nerve root that typically courses just distal to this screw head.



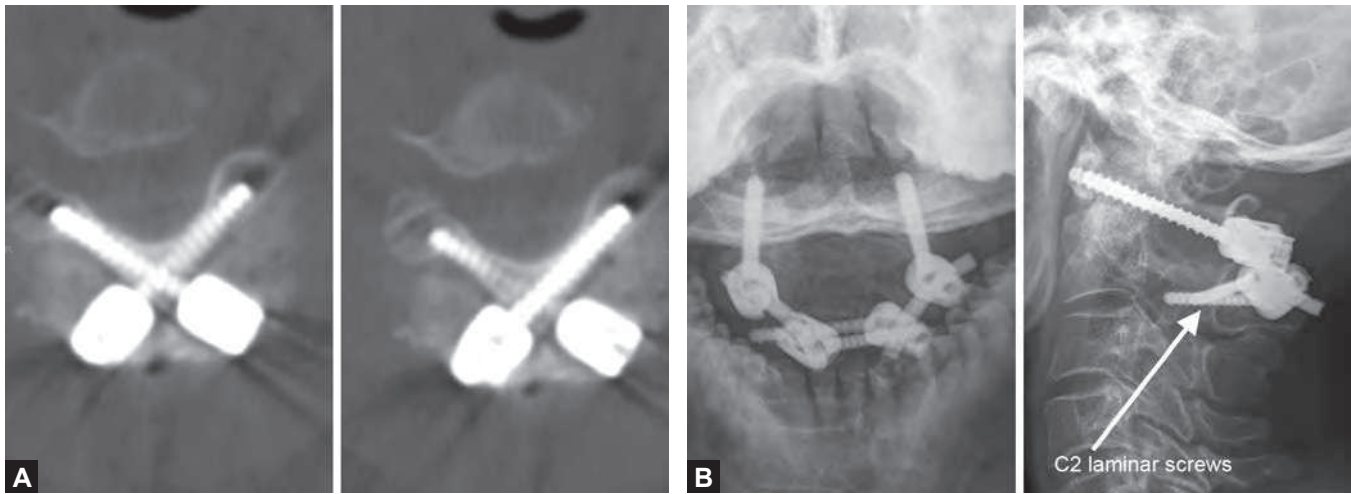
Figs. 45.8A and B: (A) Coronal and (B) sagittal anatomic specimens of the C2 anatomy demonstrating the more lateral and cranial starting point for the C2 pedicle screw (*) in comparison to the C2 pars screw.

nuances that must be taken into consideration with this value. Specifically, the anatomy of C1 lateral mass is shaped like a bow tie on a coronal view. Therefore, the O-C1 articulation extends more caudally at its medial aspect (see Figs. 45.1A and B). Therefore, C1 screw starting points should not be too medial, since this will decrease the amount of room available in the safe zone. In other words, more medial starting points will have a safe zone of 20% of the height of the anterior arch of C1, while more lateral starting point screws will demonstrate a safe zone up to 40% in order to avoid violation of the O-C1 joint.²⁷

The screw length used is usually between 25 mm and 30 mm. Occasionally, the anatomy might portend itself to longer screw lengths, but care must be taken to avoid violation of the anterior cortex by more than one to two screw threads due to the risk for injury to the internal carotid artery anteriorly.²⁸

C2 Pedicle Screw Fixation

The C2 pedicle screw can now be placed. The starting point used for the C2 pedicle screw is more proximal and medial than the C2 pars screw (Figs. 45.8A and B). As an anatomic



Figs. 45.9A and B: (A) The placement of two intralaminar screws is possible. However, as demonstrated by this anterior-posterior radiograph, (B) one screw must have a starting point slightly more cranial than the other in order to accommodate the other screw.

landmark, we define the medial border of the pedicle by following the superior border of the C2 lamina laterally. This (ventral lamina) becomes the medial wall of the pedicle and defines our medial trajectory for the pedicle screw. The starting point is 5 mm lateral to the intersection of the lamina and medial wall of the pedicle. We aim 20–25° medially and 20–25° cranially to achieve the optimal trajectory for the pedicle screw (see Figs. 45.8A and B). Generally, it is better to err medially than laterally at this level because medially, the space available for the cord allows for small medial breaches without clinical consequence. In addition, because the medial cortical wall of the pedicle is very thick, it is much less vulnerable to violation. A lateral and caudal breach, however, can result in vertebral artery injury. We notch the starting point with a burr and then switch to a cervical pedicle probe. If we encounter resistance, we use a drill with a drill stop that we sequentially lengthen, so as to prevent plunging, under hand power. We then use a ball-tipped probe to palpate for any breaches, tap and then palpate again prior to placing the screw.

C2 Intralaminar (Translaminar and Laminar) Screw Fixation

The C2 translaminar screw is an excellent alternative to C2 pedicle or pars screw fixation if the anatomy does not allow for the latter. Lehman et al. examined the pull-out strength of the C2 pedicle screw versus C2 pars screw versus the C2 intralaminar screw under salvage conditions.²⁹ The authors concluded that the pedicle screw provided the strongest

pull-out strength, while the C2 pars screw and intralaminar screw were similar, or slightly in favor of intralaminar fixation.²⁹ This screw is placed within the lamina at staggered starting points in order to allow for two screws to be placed (one in each direction) (Fig. 45.9A). One can also use one type of screw on one side and another on the contralateral side. If using bilateral laminar fixation, one must plan carefully to start the first screw as cranially as possible so that there is enough room for the second screw from the opposite side (Fig. 45.9B). In order to ensure that the screw does not violate the ventral cortex, as well as to improve fixation, one can aim for the tip of the screw to exit the dorsal cortex far laterally. Attaching a rod to a laminar screw may seem a bit difficult to someone who has never tried it. But in reality, it is quite simple, since a rod from a C1 lateral mass to a C2 screw is simply a straight line. If bilateral laminar screws are utilized, one has to limit the amount of laminar decortication for the arthrodesis, since it can weaken the screw purchase.

OCCIPITOCERVICAL FIXATION CONSIDERATIONS AND OPTIONS

There are multitudes of modern fixation options across the occipitocervical junction. One option is the occipitocervical plate/rod system, which is probably the most commonly used. Recently, occipital condyle screws were described. Lee et al. concluded that the safest method for placing the occipital condyle screw was to use a lateral starting point that was approximately 3 mm from the

midpoint aimed 40–45° medially.³⁰ This resulted in a 93% success rate for screw placement. A biomechanical study compared the use of the occipital condylar screw and traditional occipital plate/rod fixation and concluded that use of the occipital condylar screw along with a small eyelet into which a short screw was placed into the skull was similar in flexion/extension as well as lateral bending stability compared to plate/rod systems.³¹ Due to this biomechanical equivalency as well as the risk of injury to neurovascular structures when placing an occipital condylar screw (i.e. posterior condylar emissary vein, hypoglossal canal that contains the hypoglossal nerve and vertebral artery), we prefer to use plate and rod systems for occipital fusions.

When utilizing occipital fixation, it is important to ensure correct placement of the plate at the external occipital protuberance, where the bone is hardest and thickest, while avoiding skin problems. The external occipital protuberance is the second hardest bone in the body, following ones teeth. Therefore, a screw that is longer than 10–12 mm need not be bicortical to obtain great purchase. The greatest screw lengths will be those in the midline, while those more lateral will be significantly shorter. Typically screw length between 10 and 16 mm can be achieved at the midline. Tapping is essential prior to placement of occipital screws due to the extremely hard nature of the bone. Taking advantage of the anatomically favorable bone found in the midline is what modern-day occipital fixation techniques are based on. Just lateral to the midline, however, the occipital bone thins as you go more laterally and, therefore, does not provide fixation as robust as the midline. Biomechanically, this lateral bone demonstrates less pull-out strength and less insertional torque compared to their midline counterparts.³² Screw placement in the midline typically does not have to be bicortical, as the bone is mostly all cortical bone. The confluence of sinuses (the venous drainage for the cranium is the combination of the sagittal and transverse sinuses) can lead to brisk bleeding if punctured during inadvertent bicortical screw placement. In this case, calmly placing the screw in the prepared position will tamponade the bleeding and usually does not result in any clinical consequence.

When utilizing plate and rod fixation, it is our preference to utilize prebent or articulated rods instead of trying to contour our own rods. Due to the extremely high sagittal angle of the occipitoaxial angle, forming a bend that is adequate to accommodate the plate and the screws, can take multiple attempts. This can lead to notching of the

titanium rod and can predispose to rod breakage, inadequate stabilization and need for revision surgery. A titanium rod should only be bent in one direction. Unbending it in the opposite direction notches the titanium and makes it prone to early breakage. Given the long distance that this rod has to span from the plate to C1 or C2, it is already prone to breakage. Prebent rods are also typically reinforced to withstand fatigue breakage. Articulated rods are simple to use and obviate the need for complex bends.

Occasionally, the anatomy may not portend itself to C1 and occipital fixation points due to the extreme sagittal angle of the OC junction. For this reason, we prefer the posterior arch screw for C1 fixation because it usually lies more dorsal in the construct, making it easier to engage a rod that was to span C2 to the occiput. If this is still not feasible, we may skip fixation at C1 and obtain fixation at C2. It is still possible to obtain four fixation points in C2 with the aid of pars/pedicle screws and intralaminar screws.

Malalignment at the OC junction can be disabling because of setting the right length tension relationship of the esophagus and trachea as well as centering the head in the axial plane to ensure the visual fields stays centered and equal. An abnormally flexed position can make respiration and swallowing difficult. Conversely, if there is too much extension and rotation, balance and visual field problems can be disabling. We usually aim for an occipitoaxial angle between 0° and 30°.³³ More importantly, however, we use the preoperative radiographs to gauge our desired correction. If the patient is positioned at the same occipitoaxial angle as the preoperative standing radiographs, this will usually be the appropriate position for setting the OC junction.

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Instrumentation of the Subaxial Spine

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Snapshot

- » Posterior Spinous Process and Facet Wiring
- » Cervical Laminar Hooks
- » Lateral Mass Screws
- » Cervical Pedicle Screw Fixation
- » Cervical Transarticular Screw Fixation

INTRODUCTION

Cervical instrumentation began in the late 1890s. In the following century, cervical instrumentation experienced vast improvements with the development of rigid fixation including anterior cervical plates, cervical cages, pedicle screws, and lateral mass and transarticular screws. After adopting these techniques, older methods of fixation such as posterior wiring and hooks have gradually been abandoned.

POSTERIOR SPINOUS PROCESS AND FACET WIRING

In 1942, Rogers described a surgical technique for the treatment of fracture dislocations of the cervical spine in which posterior wiring and fusion were performed. This technique has subsequently been used in the last century for cervical fracture dislocations and instability. However, posterior wiring has fallen out of favor because it is limited by the presence of key portions of the posterior elements. Moreover, wiring is biomechanically not as rigid when compared to other types of instrumentation.¹

In the Rogers interspinous wiring technique, a single cable is looped through a hole at the base of the superior spinous process with the loop passing above its respective process. The free end of the cable is then passed through the inferior spinous process and the inferior loop encircles

the inferior spinous process. The cable is then tightened. In the Bohlman triple-wire technique, the first cable creates an interspinous loop in a similar manner as that of Rogers, then it is passed through separate holes in the superior and inferior spinous processes, respectively, and the ends of these cables are passed through holes in the two autologous bone grafts. The cables are then tightened. Branch et al. used methyl methacrylate, which encased the entire construct, and a standard interspinous wiring technique to treat the traumatic fracture dislocations of the lower cervical spine.² In general, posterior wiring techniques are simple to perform and use inexpensive materials. Although wiring is biomechanically inferior to screw fixation, it can effectively reconstitute the posterior tension band and can resist flexion forces in the cervical spine.

Each wiring technique carries certain risks with it. Spinous process wiring has the potential complication of penetration of the spinal canal and subsequent spinal cord injury. Care should be taken to place the starting points at the base of the spinous process. Intraoperative radiographs can be obtained before passing the wire to ensure correct placement. Facet wiring and Southwick's technique have a possible risk of nerve root and/or vertebral artery injury with the drilling and passage of the wire through the inferior facet. This risk is reduced with the placement of an instrument (Penfield #2) in the facet joint to prevent penetration of the superior process of the vertebra below.

CERVICAL LAMINAR HOOKS

Modern techniques of posterior cervical instrumentation in the subaxial cervical spine include the use of pedicle screws, lateral mass screws, and laminar hooks. These options are listed in the decreasing order of technical difficulty and biomechanical fixation strength. A comparative study found that laminar hooks performed well in resisting flexion and extension but were less effective in resisting lateral bending and axial rotation, allowing greater range of motion than screw constructs.³ Use of cervical laminar hooks has been limited by the potential for creating iatrogenic central stenosis. However, a study found that 95% of the hooks do not deform the dural sac in either the supine or prone position suggesting hooks are firmly seated and do not migrate.⁴

Indications for cervical hooks include patients with intact lamina who require posterior fixation. The

contraindications for cervical laminar hooks include trauma to the posterior cervical arch, bone tumor in the arch, spinal cord edema, or canal stenosis (when >3 segments need fixation). Studies have shown that hooks inserted in the cervical spine have a close anatomical relationship with the neuraxis, and should not be used at stenotic levels.⁴ Cervical hooks can be used individually (e.g. Halifax clamps or Apofix) or combined with pedicle or lateral mass screws.

The patient is placed in the routine prone position in Mayfield tongs. A standard midline incision is made and the lamina is exposed up to the laminofacet junction. Laminar hooks are specifically contoured to the anatomy of the cervical lamina. However, it may be necessary to sculpt the posterior lamina with a high-speed burr so that the hook fixes appropriately. Figures 46.1 to 46.6 outline the step-by-step technique for placing laminar hooks.

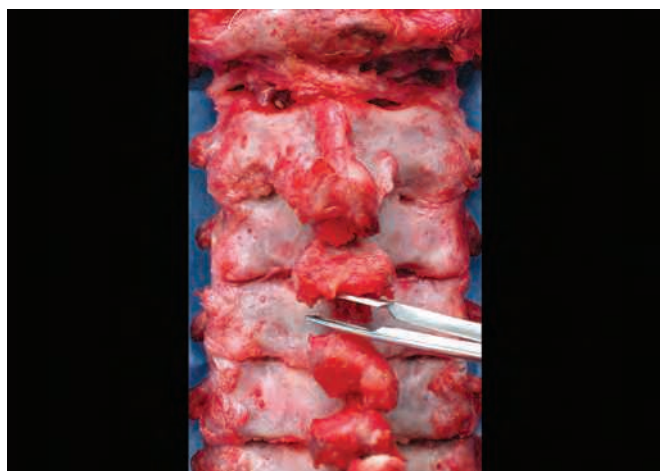


Fig. 46.1: Preparation.

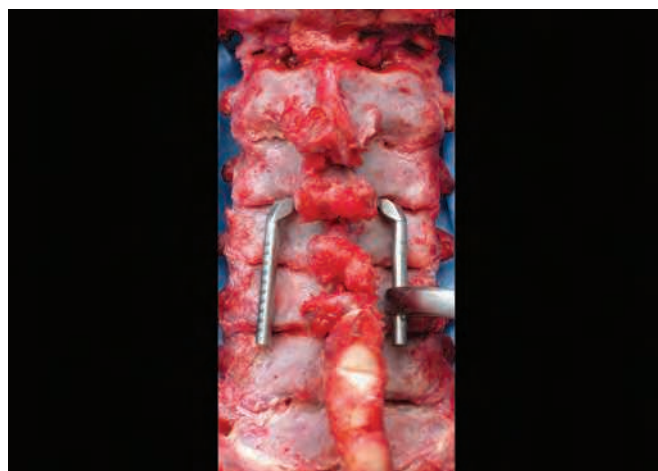


Fig. 46.2: Implantation of the cephal ends.

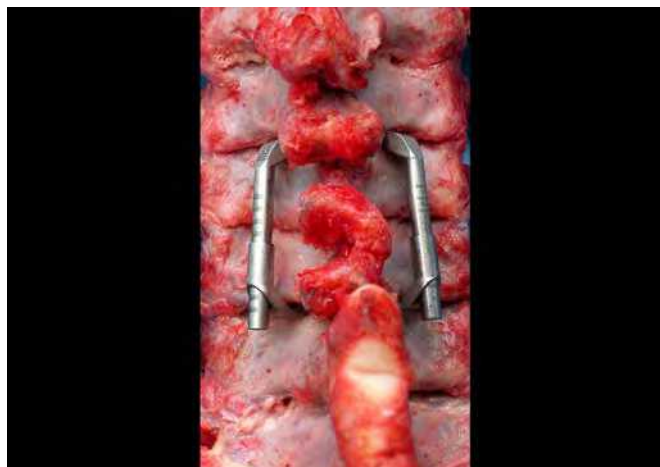


Fig. 46.3: Implantation of the caudal ends.

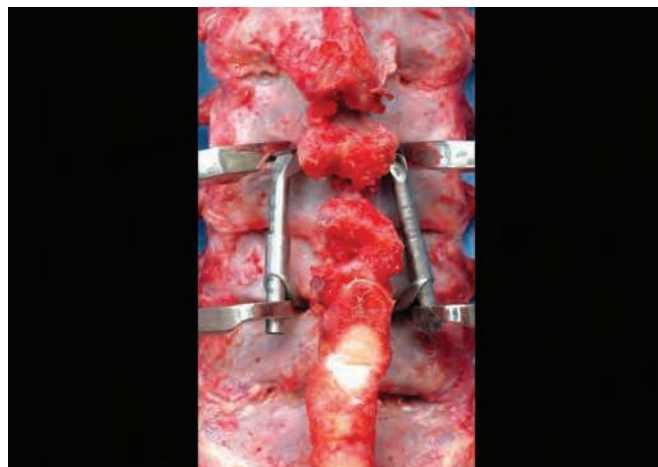


Fig. 46.4: Fastening the clamps.

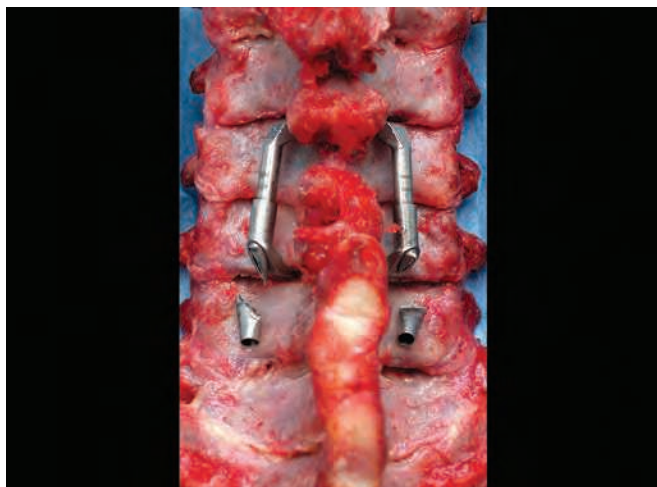


Fig. 46.5: Cutting off the prominent parts.

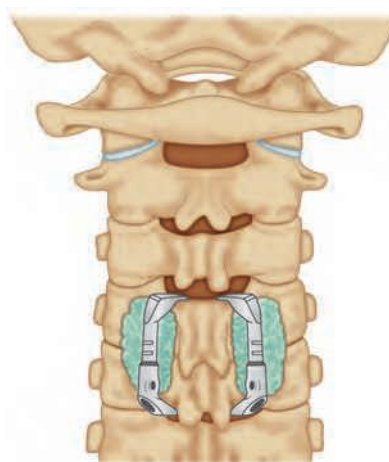


Fig. 46.6: The bone transplantation bed and the bone graft are prepared to be placed.



Fig. 46.7: The patient is placed in a prone position with the head fixed by a head fixator and the head held in a slightly flexed position.

There are a few clinical outcomes reported on the use of laminar hooks. Biomechanical studies³ demonstrated that laminar hooks appear to be a good alternative to pedicle screw fixation (PSF).

LATERAL MASS SCREWS

Lateral mass screw fixation was originally reported by Roy-Camille in the 1980s and further developed by Anderson, An, and Magerl.⁵⁻⁸ This technique has since become the mainstay of fixation in the posterior cervical spine.

Screw fixation in the lateral mass fixation can be used to treat cervical spondylosis with myelopathy,⁹ radiculopathy, traumatic injuries (including burst fracture, dislocation, tear drop fracture, unilateral facet fracture/dislocation, bilater-

al facet fracture/dislocation, lateral mass fracture, pedicle fracture, lamina fracture, etc.),¹⁰ cervical instability, neoplasm, decompression,¹¹ wide laminectomies for tumor resection or other pathologies, failure of previous fixation with other devices,¹ degenerative disorder of the cervical spine,^{10,12} congenital cervicothoracic stenosis, and deformity correction such as postsurgical kyphosis^{11,13} and cervical hyperlordosis.¹⁴

Contraindications to lateral mass fixation include comminuted, incompetent, or disconnected lateral masses resulting from trauma, excessive bony resection following a foraminotomy, or an aberrant vertebral artery.¹¹

Patients are positioned in the prone position with the head in a Mayfield clamp (Fig. 46.7). In order to aid in visualization, the shoulders are pulled down and taped to the sides of the bed. Excessive traction should be avoided as injury to the brachial plexus can occur. A standard midline posterior approach is performed exposing the lamina, facet joints, and lateral masses. It is critical to have good exposure of the lateral border of the lateral mass as well as each facet joint to be fused. A 2-mm round burr is then used to decorticate each facet joint. The center of each lateral mass is identified. It should be noted that the vertebral artery lies anterior to the center of the lateral mass. The starting point varies (Table 46.1) according to the surgeon's preference. It is the senior authors' preference to start center on the lateral mass (Roy-Camille technique). A 2-mm diameter pilot hole is then made with a burr taking care to be collinear with the other levels. The trajectory of the screw should be parallel to that of the facet joint. A Penfield #4 dissector can be placed in the facet joint to guide the cranial caudal trajectory of the screw. A drill

Table 46.1: Lateral mass screw techniques from different authors.^{1,2}

	Methods	Roy-Camille	Magerl (Figs. 46.8A to C)	Anderson	An
Entry point	Mediolateral	Midpoint	2 mm medial to midpoint	1 mm medial to midpoint	1 mm medial to midpoint
	Craniocaudal	Midpoint	2 mm cranial to midpoint	Midpoint	Midpoint
Trajectory angle	Mediolateral	0°–10° lateral	20°–25° lateral	10° lateral	30° lateral
	Craniocaudal	0°	Parallel to facet joint	30°–40° cephalad	15° cephalad

with a depth stop of 14 mm is used to drill the path of each screw in both upward and outward directions according to Magerl (Figs. 46.8A to C). Typically, the appropriate angulation involves the drill touching the spinous process of the inferior vertebrae being instrumented. Some surgeons prefer to place lateral mass screws in a bicortical manner. In this situation, a depth stop is not used as the surgeon has a tactile sensation when crossing the second cortex of the lateral mass. It should be noted that the exiting nerve is at risk when placing a bicortical screw (i.e. C5 nerve with a C5 lateral mass screw). A ball tip feeler can be used to confirm that each drilled hole has four walls prior to screw placement. Liquid Gelfoam or Floseal can also be pressurized into the tapped hole to ensure that it has a floor. Extravasation around the lateral mass or into the facet joint indicates that there may be a bony defect present. It is the senior author's preference to tap each hole prior to screw placement to avoid cracking the lateral mass during screw insertion. It is also our preference to drill and tap the lateral mass screws prior to a laminectomy to minimize passing instruments over the spinal cord during the procedure. Typical screw sizes in the lateral mass are 3.5 mm in diameter and 14 mm in length. Variable bias screw heads can be used to ease the placement of the final rod. Local autograft bone from the posterior elements mixed with allograft, if necessary, is then placed over the decorticated lateral masses and into the appropriate facet joints for the fusion following screw placement (Figs. 46.9A to O).^{9,15}

Patients are instructed to wear a rigid, semirigid, or soft collar for at least 6 weeks postoperatively. For patients with cerebral palsy, a halo-vest can be applied for at least 8 weeks followed by additional use of a semirigid collar for another 4 weeks.

Several studies report that lateral mass fixation is simple, safe, and effective^{1,15–17} compared to other fixation techniques.¹⁵ Lateral mass fixation can provide better immobilization than anterior plating¹⁷ and is associated with maintenance of alignment and a low complication

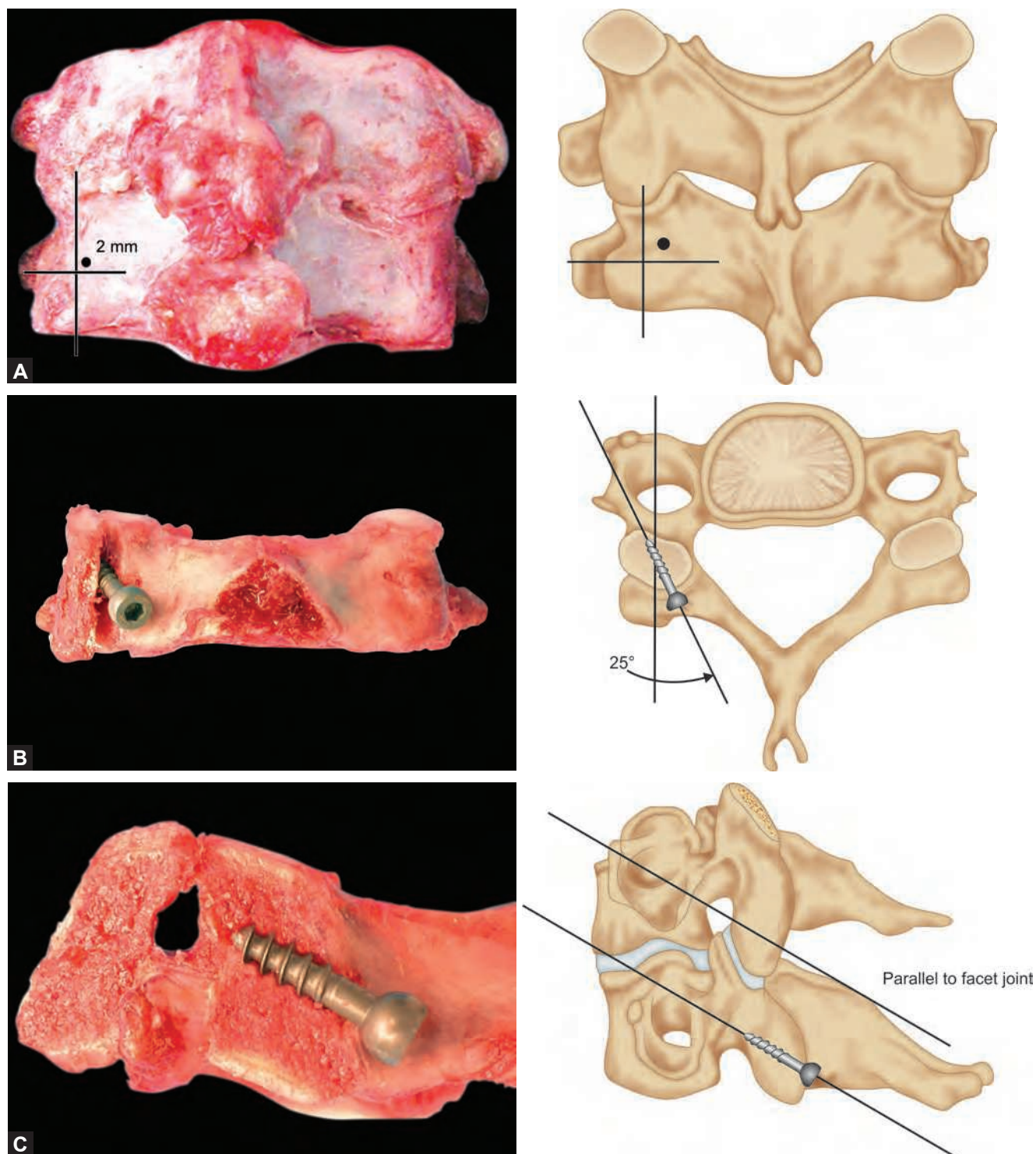
rate.^{1,10} At 14-month (4–35 months) clinical and radiologic follow-up, Wu et al. reported substantial bony fusion and good clinical results.¹ The authors caution against unilateral fixation as it creates a “hinge effect” and is less stable than bilateral fixation.¹⁸

Complications (6.2%) associated with lateral mass screw fixation include nerve root injury, spinal cord injury, facet violations, iatrogenic foraminal stenosis, vertebral artery injury, broken screw, lost reduction, pseudoarthrosis, screw avulsion, and screw loosening.^{9,19} Proper screw placement can reduce these complications. Facet violation is associated with lower trajectory angles in the sagittal plane, while violation of the vertebral artery (VA) foramen is related to lack of lateral angulation in the axial plane.¹⁵ It is necessary to preoperatively determine the location of the vertebral artery during lateral mass screw placement to minimize complications.²⁰

CERVICAL PEDICLE SCREW FIXATION

Cervical PSF was developed by Abumi et al. and has many major biomechanical advantages compared with lateral mass fixation.^{12,21–24} However, transpedicular stabilization has generally been considered a risky surgery due to the potential for serious injury to the surrounding structures, such as the spinal cord, nerve roots, and vertebral arteries.^{25,26} Authors have described different surgical techniques, including computer navigation system, to increase the accuracy of screw placement and to decrease clinical complications.

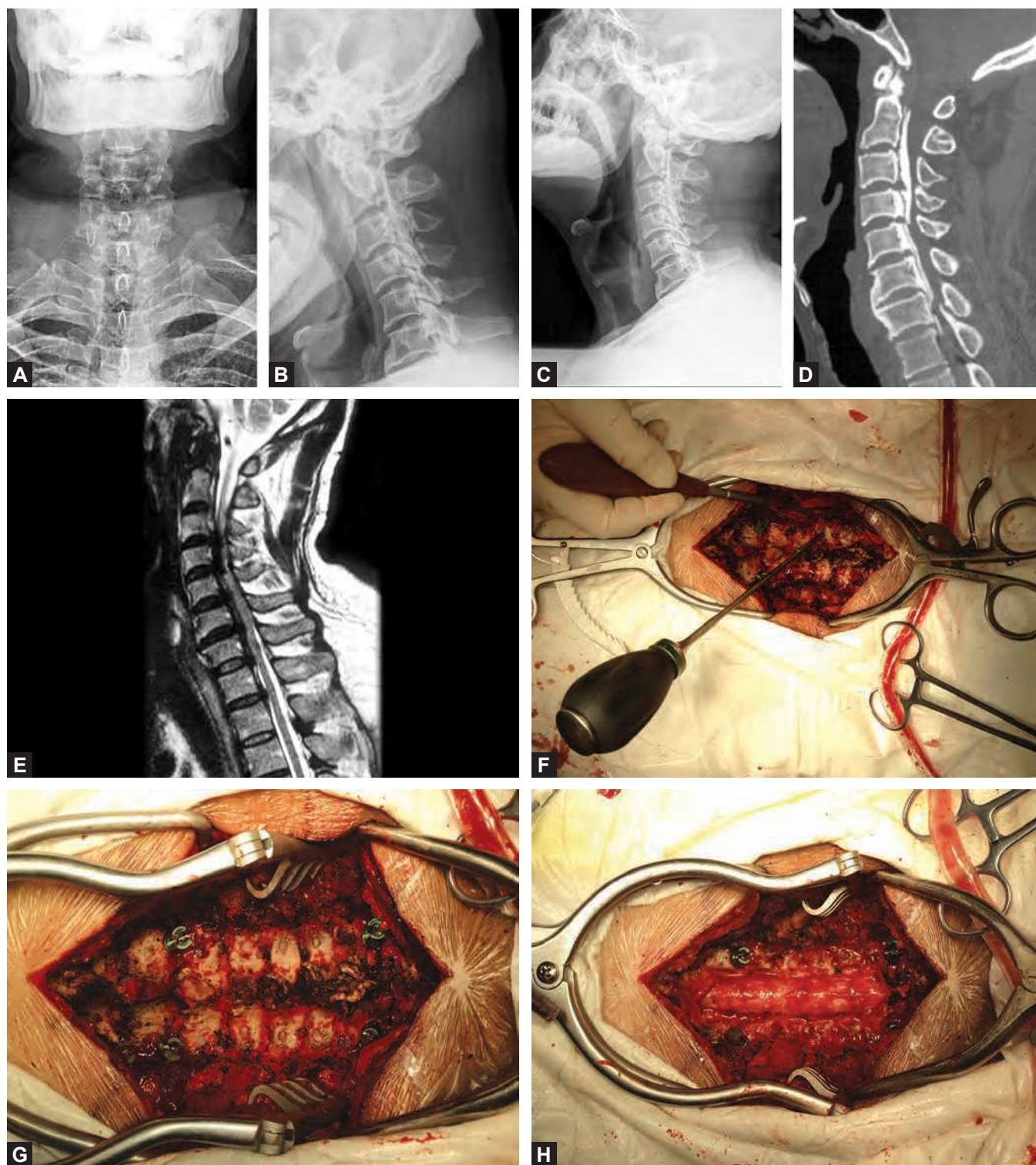
Cervical PSF has been reported to provide superior stability for reconstruction of the cervical spine.^{1,22,26–28} Unstable three-column injuries, fixation following cervical osteotomy, or postlaminectomy kyphosis are particularly suitable for cervical PSF because of its added biomechanical strengths. In patients with severe osteopenia, the strong initial fixation of pedicle screws can eliminate the necessity of postoperative halo-vest immobilization.^{29,30} Moreover, for the patients whose laminae or lateral masses are



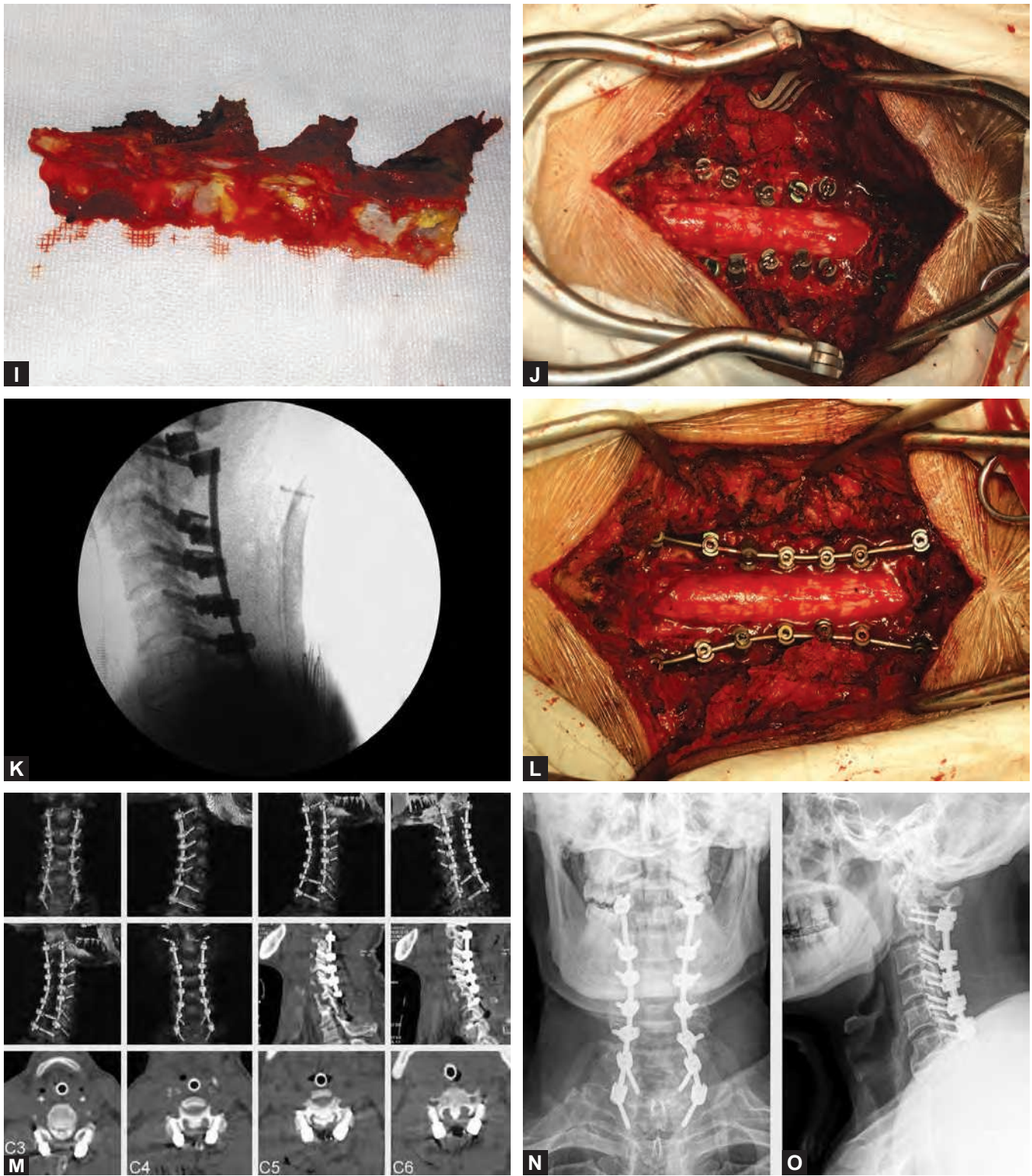
Figs. 46.8A to C: Lateral mass screws insertion using Magerl technique in cadaver specimen: (A) Entry point. (B) Horizontal screw trajectory. (C) Sagittal screw trajectory.

compromised, PSF can be particularly useful.^{28,31} Cervical PSF is a three-column fixation system with a high cor-

rection capability and low incidence of implant failure compared to conventional hook and wire constructs.³²⁻³⁵



Figs. 46.9A to H: A patient with the ossification of cervical posterior longitudinal ligament and spinal canal stenosis treated by lateral mass screws fixation with Magerl technique. (C3–C6: lateral mass screws; C2, C7, and T1: pedicle screws). (A to C) Preoperative X-ray, (D) CT, and (E) MRI showed the ossification of cervical posterior longitudinal ligament with spinal canal stenosis. (F) Exposed lateral masses and prepared the screw trajectory (right is cephalic and left is caudal). (G) After C2, C7, and T1 pedicle screws insertion, the C3–C6 lateral screw holes were drilled, tapped, and plugged up with the bone wax. (H) Laminectomy performed in C3–C7 level.



Figs. 46.9I to O: (I) Resected lamina after decompression. (J) Inserted lateral screws after decompression. (K) Fluoroscopy to confirm the screws position and whether rod contour was proper or not. (L) After fixation and local autogenous bone graft fusion. (M to O) Postoperative X-ray showed that all pedicle and lateral screws are in good positions, and cervical curvature was restored. (CT: Computed tomography; MRI: Magnetic resonance imaging).

Table 46.2: Subaxial cervical pedicle's width, height, and transverse angulation.

	Average pedicle width (mm)	Average pedicle height (mm)	Average pedicle transverse angulation (°)
C3	5.1 ± 1.1	6.2 ± 1.2	50 ± 2
C4	5.7 ± 0.9	6.4 ± 1.0	49 ± 3
C5	5.9 ± 1.2	6.3 ± 0.9	46 ± 5
C6	6.3 ± 1.1	6.5 ± 1.0	43 ± 3
C7	7.1 ± 1.0	6.5 ± 1.3	34 ± 4

Hasegawa et al. considered destructive lesions to be indications of cervical PSF. On the other hand, they noted that cervical spondylotic myelopathy and ossification of the posterior longitudinal ligament were not the indications secondary to the potential risk of vertebral artery or nerve injury.³⁶

In a systematic review, Abumi et al. concluded that infection at the posterior elements of the cervical spine, a pedicle destroyed by tumors or injuries, an absent or extremely small pedicle, a pedicle of the vertebra with major anomalies of the vertebral artery, and an extremely oblique angle of the pedicle axis from the sagittal plane are contraindications of cervical pedicle screw insertion.²⁸ The outer pedicle diameter of most cervical pedicles in previous morphometric studies is >5 mm making pedicles' screw insertion possible. Cervical pedicles that do not have a medullary canal secondary to sclerotic change or pedicles with extremely small diameters are not suited for screw insertion.²⁸

Sufficient preoperative imaging studies of the morphometric details of the cervical pedicles are critical (Table 46.2).²⁸ Onibokun et al.'s radiological and anatomical study suggests that preoperative computed tomography (CT) scans before cervical transpedicular fixation should be thoroughly analyzed for pedicle diameter, length, and direction, and tailored for each patient.³⁷ Even in the same vertebra, the diameter between the left and the right pedicle can be different depending on vertebral artery dominance. In addition, before cervical pedicle screw insertion, preoperative investigation of the course of the vertebral artery based on magnetic resonance imaging (MRI) or CT angiogram is mandatory to prevent serious complications.³⁸

A standard mindline posterior approach is used and the lateral masses are completely exposed. Identifying the starting point and trajectory in the horizontal plane is critical for correct screw placement.²⁵ Since Abumi et al.

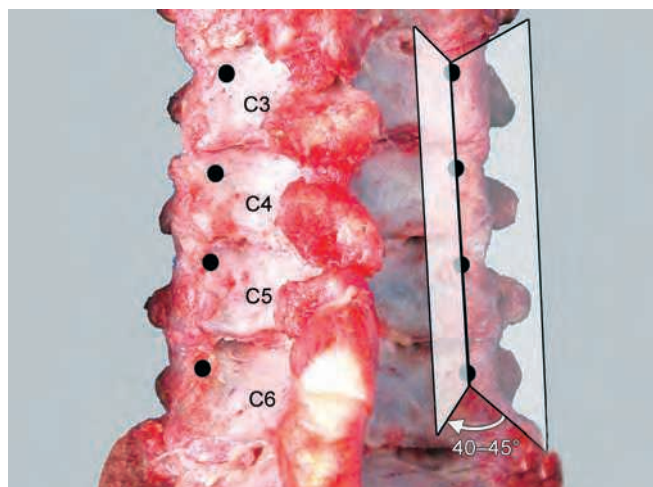


Fig. 46.10: Cadaver specimen: the technique relying on anatomical landmarks for CPS (cervical pedicle screw) insertion similar to Jeanneret and Hacker's technique for C3–C6. The entrance point is 3 mm below the superior facet joint on a vertical line in the middle of the articular mass. The drill is angled 45° medially (average 40–45°), and parallel to the contralateral lamina in axial plane and parallel to the endplate in sagittal plane.

first described cervical pedicle screw (CPS) fixation, other techniques using CT navigation have been developed and adopted to increase the safety of cervical pedicle screw placement.

Karaikovic et al. found that the location of the pedicle was unique at each cervical level.³⁹ In an anatomical study, Jeanneret et al. found that the entrance point of the pedicle is 3 mm below the superior facet joint on a vertical line drawn in the middle of the lateral mass.⁴⁰ The drill is then angled ≈45° medially, depending on preoperative CT scan templating (average 40–45°).⁴⁰ Hacker et al. suggested using the angle of the contralateral lamina as an intraoperative guide to the correct angle of medialization.⁴¹ The drill is then advanced in a line parallel to the endplate (Fig. 46.10).⁴⁰ Since the entry point at each subaxial cervical level is unique and the tolerance for error is small, using landmarks to the cervical pedicle entrance is insufficient for accurate and safe placement of pedicle screws.^{39,42,43}

A safer technique for pedicle screw placement is exposing the medial, superior, and inferior walls the pedicle by performing a laminoforaminotomy (the funnel technique).^{23,44–49} Several surgeons have advocated direct pedicle exposure.^{43,45,47–49} The pedicle-perforation rate using this technique has been reported to be 6.7%^{43,50} by Abumi et al. Using this technique, Karaikovic et al. reported that cervical pedicle screws were placed correctly (83.2%); the majority of the perforations were at C3, C4, and C5.⁴⁹

Fluoroscopy can be used as well to aid in the placement of cervical pedicle screws. The pedicle can be seen along its axis as a cortical circle on the fluoroscope. Pilot holes can then be created with a cervical drill at the center of the cortical circle. Using fluoroscopy, Zheng et al. reported an overall accuracy of 83.3% with a critical breach only 3.3% of the time.^{49,51}

Computed tomography guidance and the use of navigation can also be useful when placing cervical pedicle screws.^{44,47,52-56} Several studies have shown that navigation provided a higher accuracy of screw placement with less radiation exposure compared to conventional methods particularly in a deformed or pediatric cervical spine.⁵⁷⁻⁶¹ There are several navigation systems available for cervical pedicle screw placement. Two-dimensional fluoroscopic navigation is inexpensive and easy to operate; however, it does not provide axial images making it unsuitable for the cervical spine.^{62,63} Intraoperative CT (iCT) navigation systems have many advantages and eliminate almost all of the drawbacks of other navigation systems.⁶⁴⁻⁷⁰ These systems are highly accurate, have short data acquisition times, and do not require surgeon-dependent registration or open spinal exposure.^{64-66,69,70} Radiation exposure and cost are the main limitations of an iCT navigation system.⁷¹ Hott et al inserted 96 screws in 30 patients and reported that only 2 screws perforated the cortex (Figs. 46.11A to L).

The vertebral artery typically enters the cervical spine through the C6 transverse foramen. As such, placement of a C7 pedicle screw is distinctly different from the placement of pedicle screws at C3–C6. In addition, the average pedicular width and height of C7 are also larger measuring 6 mm and 5.8 mm, respectively.⁷² Prior to placing C7 pedicle screws, preoperative axial CT and MRI studies need to be considered to ensure that the vertebral artery does not enter at C7. The CT scan can also be used to measure the dimensions and angulation of the C7 pedicle. The average pedicle angulation of C7 in the transverse plane is 33.3°.⁷² The starting point is typically just caudal to the C6/C7 facet joint and slightly lateral to the midline of the lateral mass (Figs. 46.12A and B).²⁸ The relationship of the starting point with the C6/C7 facet can be verified on the sagittal CT view of the C7 pedicle. Despite the relatively larger size of the C7 pedicle, Barrey et al. assess the feasibility of C7 pedicle screw placement using anatomical guidelines alone and found that morphological guidelines were not sufficient to ensure safe screw placement. The authors recommended performing a laminoforaminotomy with direct palpation of the pedicle.⁷²

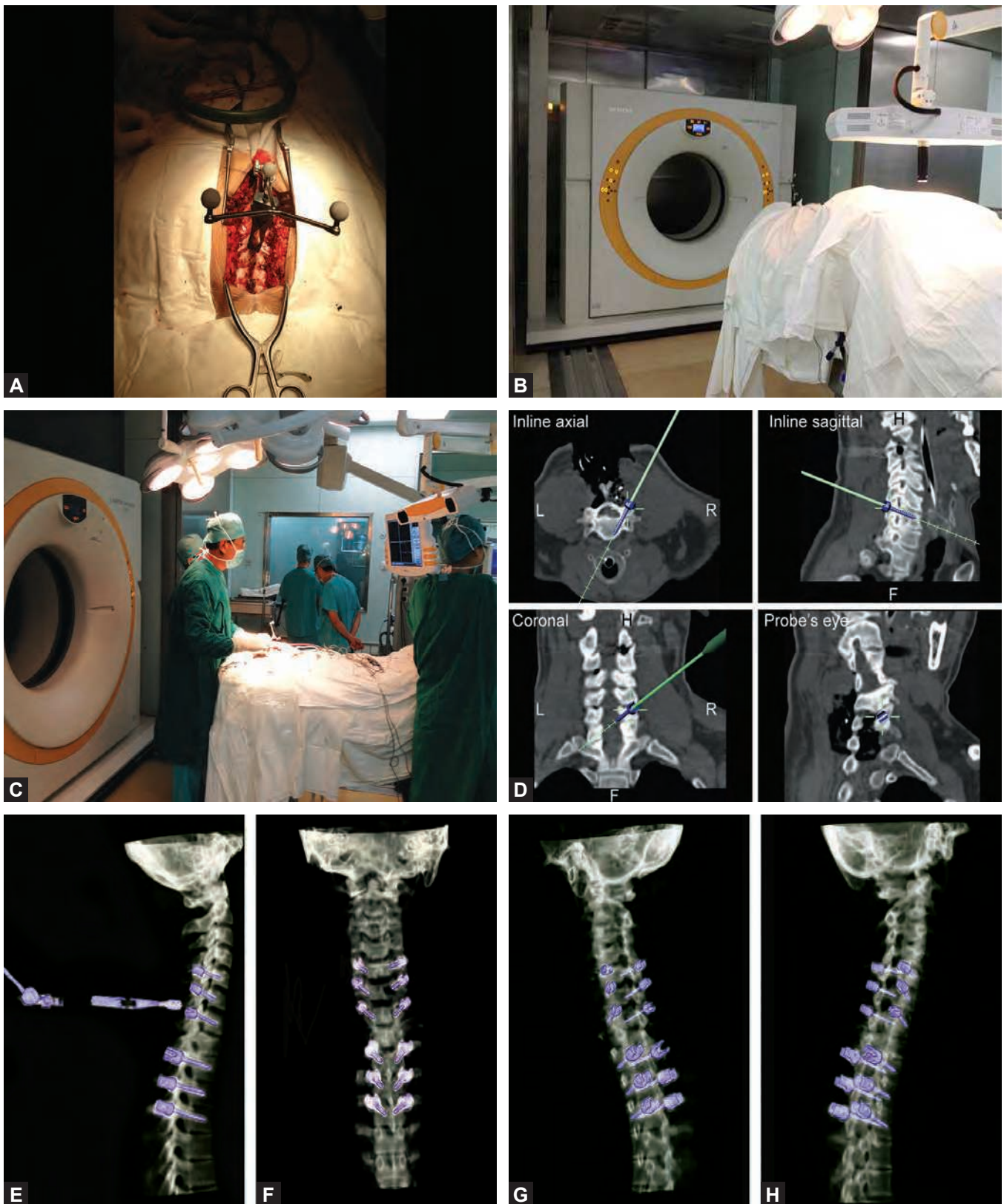
Typically, after the screw path is drilled and tapped, a 3.5-mm diameter by 18–24-mm length screws are appropriate for C3–C7.²⁸ Following screw placement, meticulous decortication of the facets and lateral masses should be performed with a burr for bone fusion.²⁵

Intraoperative neurological monitoring using motor evoked potential (MEP), somatosensory evoked potential (SSEP), and free running electromyogram (EMGs) is critical for assisting in the accuracy and safe placement of cervical pedicle screws.^{73,74} Djurasovic et al. found that EMG stimulation thresholds of >15 mA reliably predicted acceptable screw position. Values below 10 mA were associated with screw malposition and required exploration and potential removal.⁷⁵

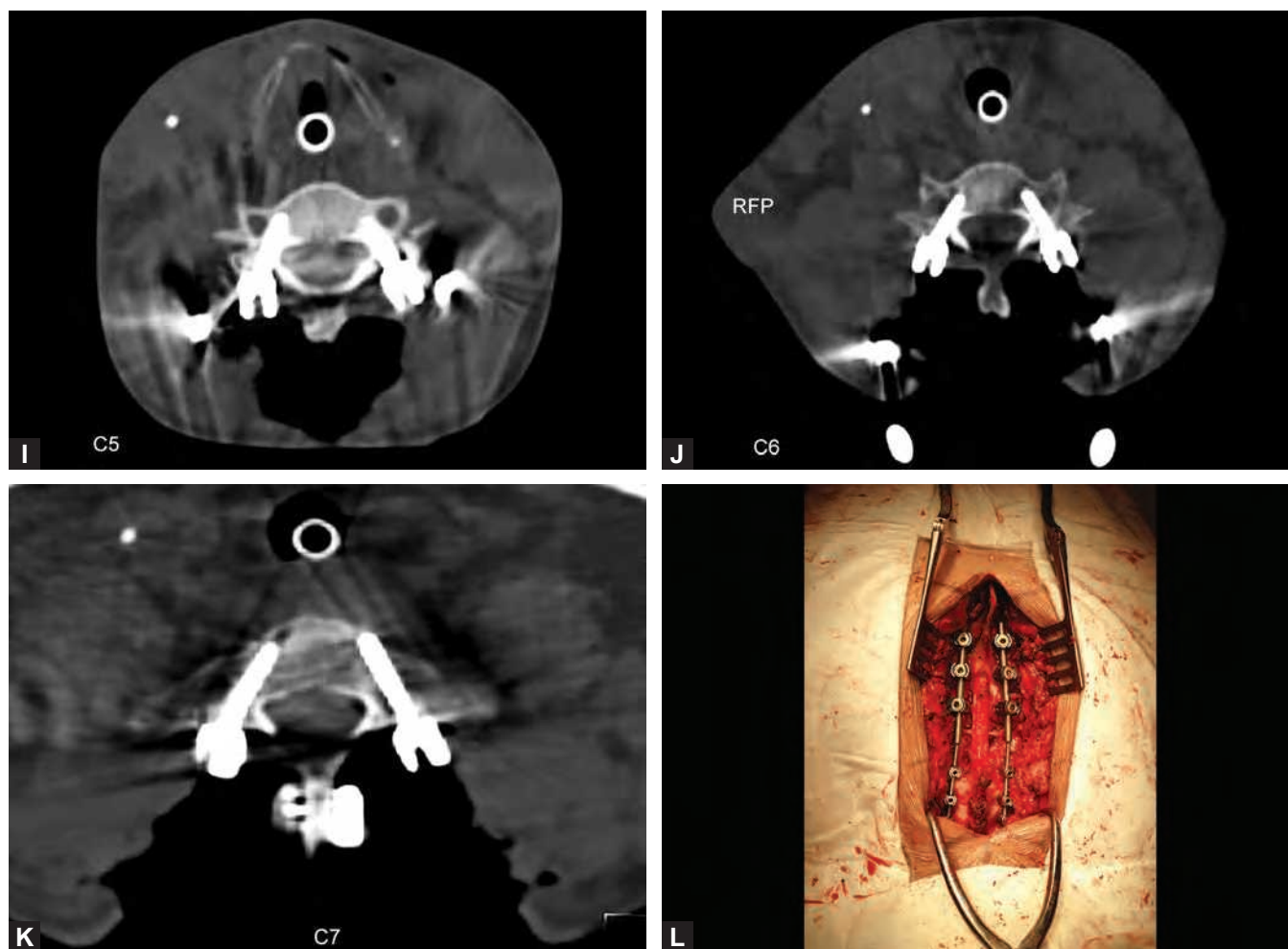
Numerous studies have reported on the ability for cervical pedicle screws to help in achieving high fusion rates with excellent correction of cervical deformity.^{31,50} Abumi et al. report that solid bony fusion was obtained in all patients except in those with metastatic tumor who did not receive bone grafting.³¹ Yukawa et al. reported that 100 consecutive patients with unstable cervical spine injuries underwent cervical PSF with only 2 cases of instrumentation failure and loss of correction. A solid posterior fusion was achieved in 95% of patients.²⁶

Despite numerous studies on the biomechanical benefits and superior correction of cervical deformity with cervical PSF, possible injury to the vertebral artery and nerve roots is of concern.²⁸ The complicated anatomy of the cervical spine and the variation of pedicle anatomy have been associated with a relatively lower accuracy and higher risk of severe neurovascular complications when compared to other regions of the spine.⁷⁶ A medially placed screw could injure the spinal cord while a laterally placed screw could injure the vertebral artery. An inferiorly or superiorly placed screw could injure the exiting nerve root.

Yukawa et al. reported a 3.9% pedicle perforation rate with 1 vertebral artery injury in 144 patients.²⁵ Abumi et al. reported a 6.7% pedicle perforation rate with 1 vertebral artery injury in 180 patients. However, other authors have reported up to a 30% malposition rate (including 9% critical breach rate)⁷⁷ and a 3.4% vertebral artery injury rate.^{36,77} As a result, some authors have advised that midcervical pedicle screws posed significant additional risk and should only be placed by very experienced spine surgeons in the setting of destructive lesions only.^{36,77} Less-experienced spine surgeons should perform cervical pedicle screw insertion with the assistance of experienced surgeons.⁴³



Figs. 46.11A to H

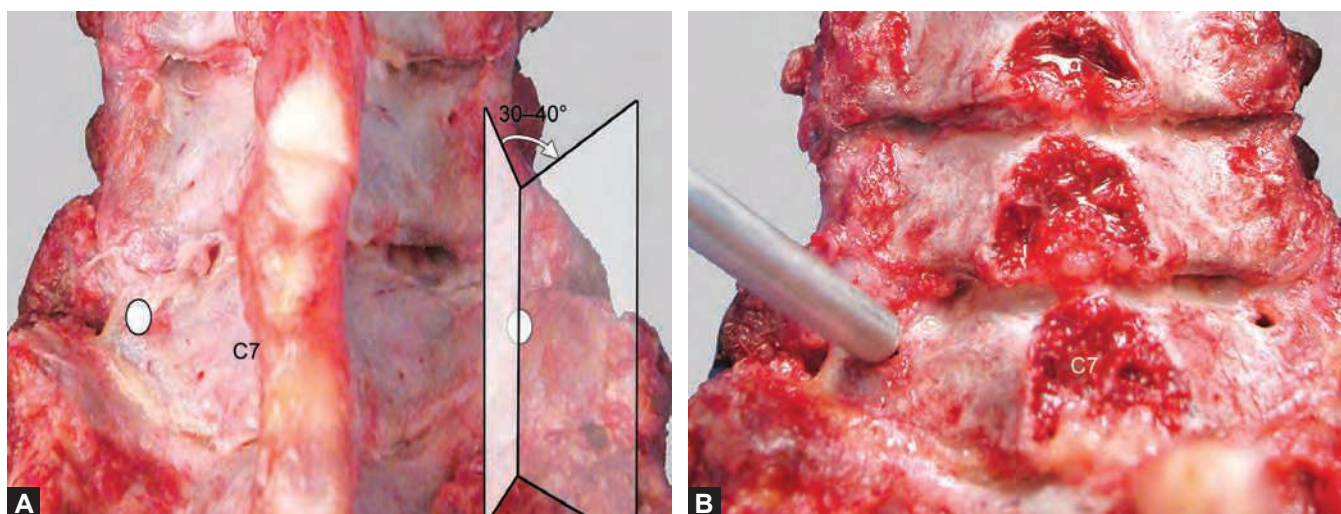


Figs. 46.11A to L: The patient with cervicothoracic metastatic carcinoma was treated with decompression and pedicle screw fixation (C5–T4). (A) A reference array was attached to the spinous process. (B) The iCT scan was then obtained and transferred to the image-guidance workstation. (C) After automatic registration, the surgeon checked the accuracy of navigation by the bony landmark. If the accuracy of navigation was unacceptable or doubted during the operation, additional CT scan and registration were necessary until the accuracy of navigation was acceptable. (D) The surgeon drilled, tapped, and placed the instrumentation under the iCT navigation guidance of three-dimensional, coronal, axial, sagittal, and probe's eye view. After all pedicle screws were placed, the accuracy of placement of all pedicle screws was first assessed by an iCT control scan. Different 3D CT images show that the all the pedicle screws were implanted exactly in the pedicles. (E) Lateral CT image with a reference array attached to the adjacent spinous process. (F) A-P (anterior posterior) CT image. (G) Oblique CT image (right). (H) Oblique CT image (left). (I) Axial CT image (C5). (J) Axial CT image (C6). (K) Axial CT image (C7). (L) Postfixation image. (iCT: Intraoperative computed tomography).

CERVICAL TRANSARTICULAR SCREW FIXATION

Roy-Camille and Saillant pioneered the use of transarticular screw fixation in the subaxial cervical spine in 1972.⁷⁸ Although it has not been widely adopted, facet screw fixation has been used by a select few surgeons over the last several decades.⁷⁹ Takayasu et al. and Xu et al. have reported the safe placement of cervical transarticular screws (Figs. 46.13 and 46.14).⁸⁰

Transarticular facet fixation is applicable to trauma, posterior fixation following laminectomy, posterior fixation following anterior cervical surgery,⁷⁸ and as a salvage technique for failed lateral mass fixation.¹¹ Transarticular screw fixation can also be used in conjunction with other posterior fixation techniques including posterior wiring techniques.¹¹ It should be noted that in biomechanical studies, stand-alone transfacet screw fixation was found to be inferior when compared to lateral mass screw



Figs. 46.12A and B: The entrance point is just caudal. The entrance point is just caudal of the C6/C7 facet joint and slightly proximal to the notch in the craniocaudal direction. The drill is angled 35° medially (average 30-40°) and parallel to the endplate in sagittal plane.

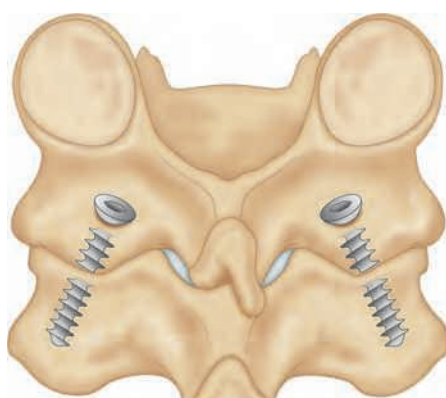


Fig. 46.13: Views of transarticular facet screws in the cervical spine. Source: DalCanto RA, Lieberman I, Inceoglu S, et al. Biomechanical comparison of transarticular facet screws to lateral mass plates in two-level instrumentations of the cervical spine. *Spine (Phila Pa 1976)*. 2005;30(8):897-2.

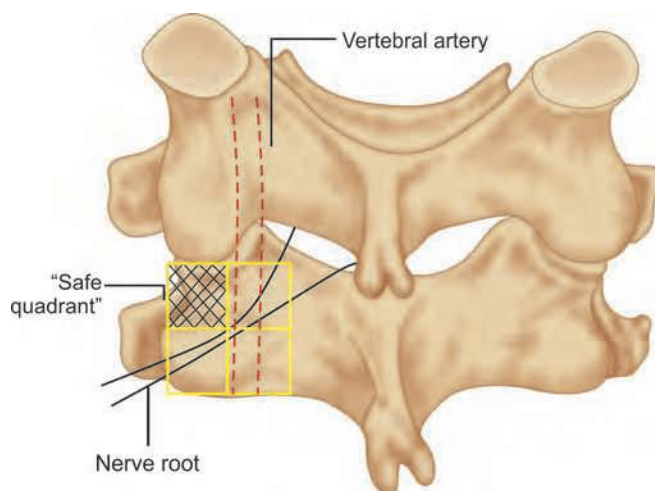


Fig. 46.14: The "safe quadrant" of the articular pillar. There are no artery or nerve root courses.

fixation.⁸¹ However, transarticular screws have greater pullout strength secondary to multicortical fixation.⁸²

Transarticular screw fixation can be used in all but the most in a caudal segment of a fusion. DalCanto et al. described the starting point as 2-mm caudal to the mid-point of the lateral mass with a 40° caudal and a 20° lateral angulation. The screw should traverse as perpendicular as possible to the articular surface. Jost et al. reported the mean optimal medial-lateral insertion angles [\pm standard deviation (SD)], mean sagittal insertion angles, and

the mean trajectory lengths (Table 46.3).⁷⁸ Navigation and/or fluoroscopy can be used to guide transarticular screw placement.⁸³⁻⁸⁵

Clinical studies have shown that after an average of 6 months, there were no signs of hardware failure.⁸⁶ Long-term follow-up (3 months to 5 years) continued to show no hardware failure with good fusion rates.⁸⁰

Complications associated with transarticular screw placement in the subaxial cervical spine include injury to the spinal cord, vertebral artery, or nerve root.

Table 46.3: The mean optimal mediolateral insertion angles (\pm standard deviation), the mean sagittal insertion angles, and the mean trajectory lengths.

	Mean optimal mediolateral insertion angles (°)	Mean sagittal insertion angles (°)	Mean trajectory lengths (mm)
C2–C3	23 \pm 5	77 \pm 10	15 \pm 2
C3–C4	24 \pm 4	77 \pm 10	14 \pm 1
C4–C5	25 \pm 5	80 \pm 11	15 \pm 1
C5–C6	25 \pm 4	81 \pm 8	16 \pm 2
C6–C7	33 \pm 6	100 \pm 11	23 \pm 4

In addition, if a screw is placed too close to the caudal edge of the inferior facet, a small portion of the inferior facet below the screw could fracture.⁸⁷

KEY POINTS

- Knowledge of cervical anatomy is critical to instrumenting the subaxial cervical spine. Preoperative planning of screw sizes and trajectories as well as vertebral anatomy using CT or MRI should be performed before every case.
- Understanding contraindications to certain types of fixation methods is important. Fractures of the lateral mass or pedicle should be identified preoperatively for surgical planning.
- Placement of cervical pedicle screws is possible when performed by experienced surgeons. The complications of cervical pedicle screw placement (C3–C6) can be catastrophic and the benefit must be weighed against the risks of the procedure. We advocate that if the vertebral artery is not within the C7 transverse foramen, then pedicular screw fixation of C7 is generally safe.
- Use of navigation can be useful in the cervical spine and can avoid hardware malplacement, particularly in the cervical pedicles.

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- This article describes a retrospective operative review of a total of 1,026 lateral mass screws that were placed in 143 patients. This study demonstrates lateral mass screw fixation is a safe and effective stabilization technique.
- Abumi K, Ito M, Sudo H. Reconstruction of the subaxial cervical spine using pedicle screw instrumentation. *Spine (Phila Pa 1976)*. 2012;37:E349-56.
- This article provides an excellent overview of the indications, detailed techniques, and complications of cervical PSF. Preoperative imaging studies and strict control of screw placement during fixation can minimize neurovascular complications.

Surgical Treatment of Congenital Foramen Magnum Lesions: Transoral Approach and Foramen Magnum Decompression

Paolo Perrini, Nicola Di Lorenzo, James A Sanfilippo

Snapshot

- » Treatment Paradigm
- » Transoral Approach
- » Postoperative Instability
- » Foramen Magnum Decompression

INTRODUCTION

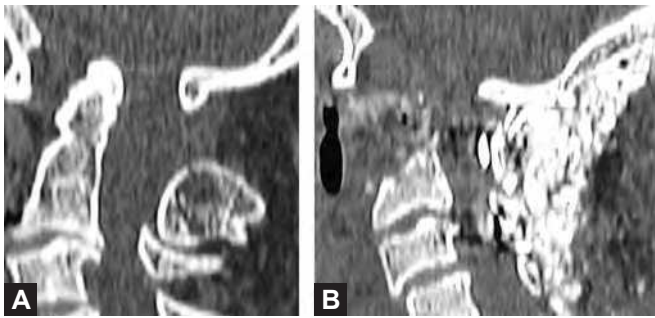
Congenital lesions of the craniovertebral junction (CVJ) had long gone unrecognized. It was only after Chamberlain's seminal radiographic investigations in 1939 that basilar invagination and the other bony abnormalities of the CVJ were considered for antemortem diagnosis and treatment.¹ These lesions were initially managed by a posterior osteodural craniocervical decompression with dismal overall clinical results.²⁻⁴ In fact, when an irreducible, cranially translated, or posteriorly dislocated odontoid peg compresses the cervicomedullary junction ventrally, posterior decompression alone cannot be relied on to improve the prognosis of patients. In such a particular anatomical scenario, the posterior approach can provide only partial decompression, usually leading to an increase in ventral cervicomedullary junction compression.⁵

The transoral approach (TOA) originally described by Kanavel in 1917⁶ and subsequently refined through the contributions of many different pioneers^{4,7-11} can be regarded today as the standard approach for the treatment of irreducible anterior abnormalities that compress the cervicomedullary junction. Over time, the value of a straight anterior approach to extradural lesions of CVJ has been widely accepted, and variations of the TOA including the maxillary dropdown procedures have been described in patients with severe basilar invaginations or in cases of limited jaw mobility.^{5,8,12}

In this chapter, we describe the pearl and pitfalls of a standard TOA for CVJ malformations and the circumstances in which the TOA requires additional posterior craniocervical decompression.

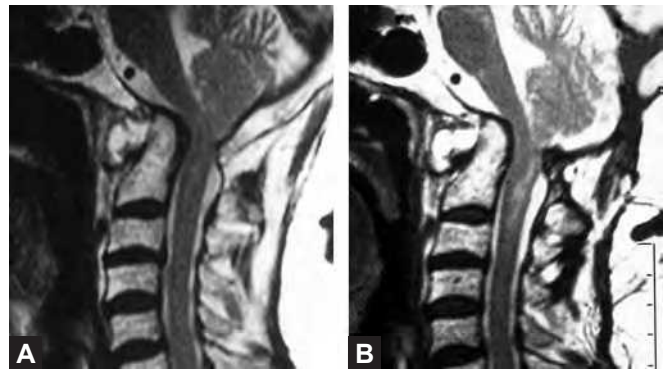
TREATMENT PARADIGM

The factors dictating the surgical strategy in patients with CVJ malformations should be carefully evaluated preoperatively.^{4,11} First, the reducibility of the malformation should be investigated with spinal radiography and computed tomography (CT) scan, including dynamic flexion and extension views. Second, the site of encroachment (anterior or posterior) should be established. The indication for a TOA is irreducible ventral compression at the cervicomedullary junction (Figs. 47.1A and B). In the rare instances of fixed posterior compression, a standard foramen magnum decompression (FMD) is mandated. The primary treatment of a reducible CVJ malformation is posterior fixation and fusion. The extent of mandibular excursion and the severity of basilar invagination dictate the adjuncts to the TOA (i.e. the transmaxillary approaches).⁵ In our experience, a LeFort I Osteotomy is required in patients with platybasia and severe basilar invagination (odontoid tip projecting ≥ 20 mm above the Chamberlain's line).⁵ In addition, we favor the use of the open-door maxillotomy approach in patients with limited jaw mobility (i.e. an interdental space ≤ 30 mm).⁵



Figs. 47.1A and B: (A) Preoperative and (B) postoperative sagittally reformatted computed tomography scans, revealing basilar invagination, atlas assimilation, and atlantoaxial dislocation. The patient underwent single-stage transoral decompression and posterior occipitocervical fixation. The postoperative computed tomography scan shows removal of the odontoid with sparing of the anterior ring of the atlas. Onlay local autologous bone and iliac crest autograft was laid on the decorticated suboccipital surface and cervical vertebrae to promote solid fusion.

Congenital abnormalities of the CVJ occur in 30–50% of patients with Chiari I malformations.^{13–15} The surgical treatment of tonsillar herniation in the presence of irreducible ventral compression is still controversial. Recent literature suggests that a standard FMD in patients with fixed ventral encroachment and tonsillar prolapse is consistently associated with early, or more often, delayed neurological worsening (Figs. 47.2A and B).^{5,16} Symptomatic progression after FMD is due to further tonsillar prolapse (i.e. tonsillar ptosis) or an increase in ventral compression. According to our surgical experience, corroborated by recent literature,¹⁶ we suggest that an anterior decompression is effective in relieving obstruction of the subarachnoid space at the foramen magnum level in most patients with Chiari malformation associated with fixed CVJ malformation (Figs. 47.3A to C). This surgical treatment philosophy is based on the understanding of the critical role played by ventral compression at the CVJ level in the overcrowding of the posterior cranial fossa. After a generous anterior decompression, the ascent of the cerebellar tonsils into the posterior fossa with acquisition of a more rounded shape can generally be observed in most of patients. After the TOA for malformations of the CVJ, the risk of creating acute or delayed spinal instability is invariably high. In order to mobilize the patients as soon as possible, we have moved from performing a planned posterior fixation as a second procedure, to single-anesthesia transoral decompression and subsequent posterior occipitocervical fixation.



Figs. 47.2A and B: (A) Preoperative and (B) postoperative mid-sagittal T2-weighted magnetic resonance imaging of a patient with basilar invagination, fixed atlantoaxial dislocation, posterior atlas assimilation, severe brain stem compression, and hindbrain herniation. The patient underwent posterior fossa decompression (PFD) before referral to our unit. He experienced delayed deterioration in motor function 16 months after PFD. The postoperative MR scan disclosed a wide suboccipital craniectomy, increase in ventral brain stem compression, and the appearance of high-signal intensity at the cervicomedullary level. This case demonstrates that patients with irreducible or partially reducible craniovertebral junction malformations can develop delayed spinal instability after PFD with resultant increase in ventral cervicomedullary junction compression.

TRANSORAL APPROACH

Preoperative Assessment and Anesthesiological Considerations

The TOA can be performed when an interdental working distance of at least 30 mm is available. In cases of limited temporomandibular jaw mobility, a transmaxillary procedure should be considered. Instead of preoperative nasal and oropharyngeal culture, we favor the use of intravenous prophylactic ceftriaxone, which is continued for 24 hours postoperatively. A complete dental assessment is mandatory since transoral surgery is contraindicated in case of an active nasopharyngeal infection. A mandatory tracheostomy, routinely used early in our experience, has been replaced by fiberoptic nasotracheal intubation. We reserve prophylactic tracheostomies for the extended maxillo-tomy approach and in patients with brain stem compromise requiring prolonged ventilation.

Operative Positioning

The patient is positioned supine, with the skull rigidly placed in a three-pin fixation system. The head is extended from 10° to 15° according to the severity of basilar



Figs. 47.3A to C: (A) Preoperative midsagittal T2-weighted magnetic resonance imaging (MRI) scan of a symptomatic 64-year-old woman, revealing basilar invagination, atlas assimilation, hindbrain herniation, and cervical syringomyelia. (B) Early postoperative sagittally reformatted computed tomography scan after transoral decompression and occipitocervical fixation. No craniocervical decompression was performed. (C) Postoperative midsagittal T2-weighted MRI scan obtained at 3 months demonstrates relief of the cervicomedullary compression, ascent of the cerebellar tonsils, and shrinkage of the syrinx. This case clarifies that transoral approach achieves effective decompression of the cervicomedullary junction and, in turn, disimpacts the cerebellar tonsils with resultant syringomyelia resolution.

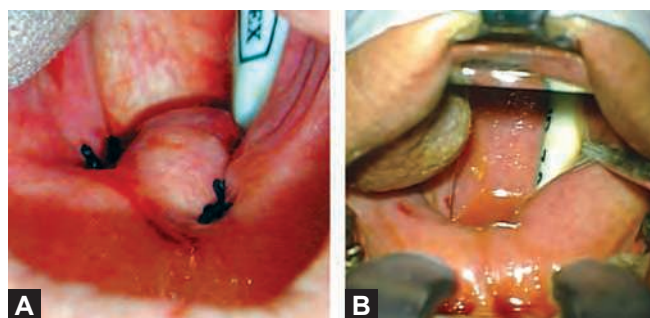
invagination. Positioning the patient in this manner helps the surgeon improve visualization of the pathology. The surgeon is seated at the top of the patient's head, and the surgery is fully performed with the aid of a binocular surgical microscope.

Instrumentation

A dedicated transoral system (Crockard transoral instruments, Codman Raynham, MA) including an oral/tongue depressor, attachable retractors, and extra-long instruments is the prerequisite for a safe and effective surgery. The retraction of the soft palate can be effectively obtained with two rubber catheters inserted through the nostrils and stitched laterally to the uvula (Figs. 47.4A and B).^{17,18} This maneuver greatly improves the exposure of the oropharynx and avoids the soft-palate splitting. Neuronavigation techniques or simple intraoperative fluoroscopy is used to provide confirmation of anatomic landmarks during the transoral procedure.

Operative Procedure

The procedure begins with infiltration of the posterior pharynx, with 1% lidocaine with epinephrine to facilitate dissection. Lateral fluoroscopy is used to confirm the position of the anterior tubercle of the atlas, which can be



Figs. 47.4A and B: Retraction of the soft palate. (A) Two rubber catheters inserted through the nostrils are stitched laterally to the uvula. (B) Traction of the catheters allows retraction of the soft palate, improving the exposure of the oropharynx.

easily palpated transorally, as well as to assess the cranio-caudal exposure obtained after positioning of the retractor system (Fig. 47.5). The identification of the anterior tubercle aids to maintain a midline trajectory. A linear midline incision of 2 cm in length along the median raphe of the posterior pharyngeal wall is carried through the mucosa and pharyngeal muscles (Fig. 47.6A). Monopolar cauterization is used to dissect the longus colli muscles and the anterior longitudinal ligament and to extend the dissection laterally from the anterior surfaces of C1 arch, the C2 vertebral body, and the lower clivus (Figs. 47.6B and C). The single-layer tissue flap is maintained laterally with

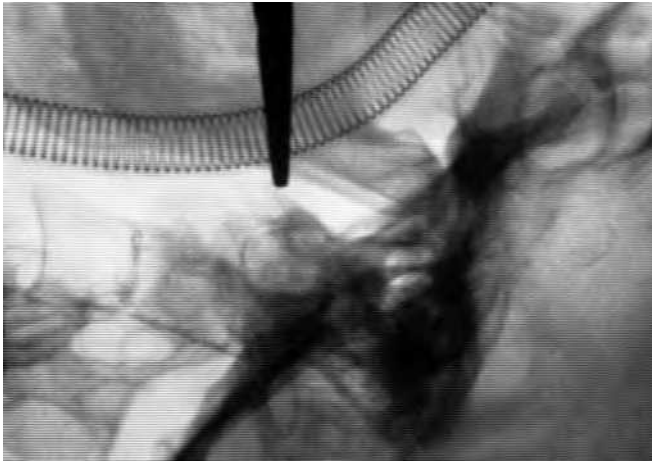


Fig. 47.5: Intraoperative lateral fluoroscopy of cervical spine demonstrating the identification of anterior tubercle of C1, which is the main landmark during the transoral approach to craniovertebral junction malformations.

tooth-bladed pharyngeal retractors. Bony resection is performed with small diamond and cutting burrs (Fig. 47.6D). Early in our experience, we aggressively removed the anterior arch of C1 to expose and progressively resect the odontoid peg in a piecemeal fashion. We now attempt to preserve the integrity of the anterior arch of C1 as much as possible, drilling the base of the dens and working inferiorly to the C1 arch. This bottom-up C1-sparing drilling technique generally requires removal of the inferior rim of the anterior arch of C1 to provide the effective angle of resection to the invaginated odontoid.¹⁹ When the base of the dens is transected, the odontoid is grasped with an odontoid rongeur and pulled inferiorly. This maneuver allows the surgeon the ability to sharply dissect and cut the alar and apical ligaments without pressure on the cervicomedullary junction and to remove, in an en bloc fashion, the invaginated odontoid (Figs. 47.6E and F). In fact, only after sectioning of the crucial ligament, can a proper dural protrusion into the operative field be appreciated (Fig. 47.6G). In patients with severe basilar invagination, this technique cannot be safely performed. In these patients the removal of the anterior arch of C1 is required to expose and remove the offending odontoid peg using the piecemeal technique. Transoral decompression ends when the pulsating dura mater protrudes into the surgical decompression site. After decompression, hemostasis is achieved and a piece of antibiotic wax is placed on the operative field against the dura; the mucosa and pharyngeal muscles are closed in a single layer with interrupted absorbable sutures (Fig. 47.6H).

Postoperative Management

Postoperatively, patients are transferred to the intensive care unit, where the endotracheal tube is maintained for 12–18 hours, depending on soft-tissue swelling and respiratory function. For the first 3 days after surgery, the patient should maintain an NPO (nothing by mouth) status, and nutrition should be administered intravenously. We do not favor the use of a nasogastric tube for enteral feedings. Periodic administration of hydrocortisone ointment to the lips helps to minimize postoperative swelling. Broad-spectrum antibiotics are administered for the first 72 hours. Patients are mobilized within 48 hours, and prophylaxis of postoperative deep vein thromboembolism with low-molecular-weight heparin is administered until they are fully ambulatory. A plain X-ray and a CT scan are obtained before discharge to evaluate the correct position of occipitocervical fixation and adequate CVJ decompression. The patients are placed in a rigid collar (Philadelphia collar) for 3 months.

Potential Complications

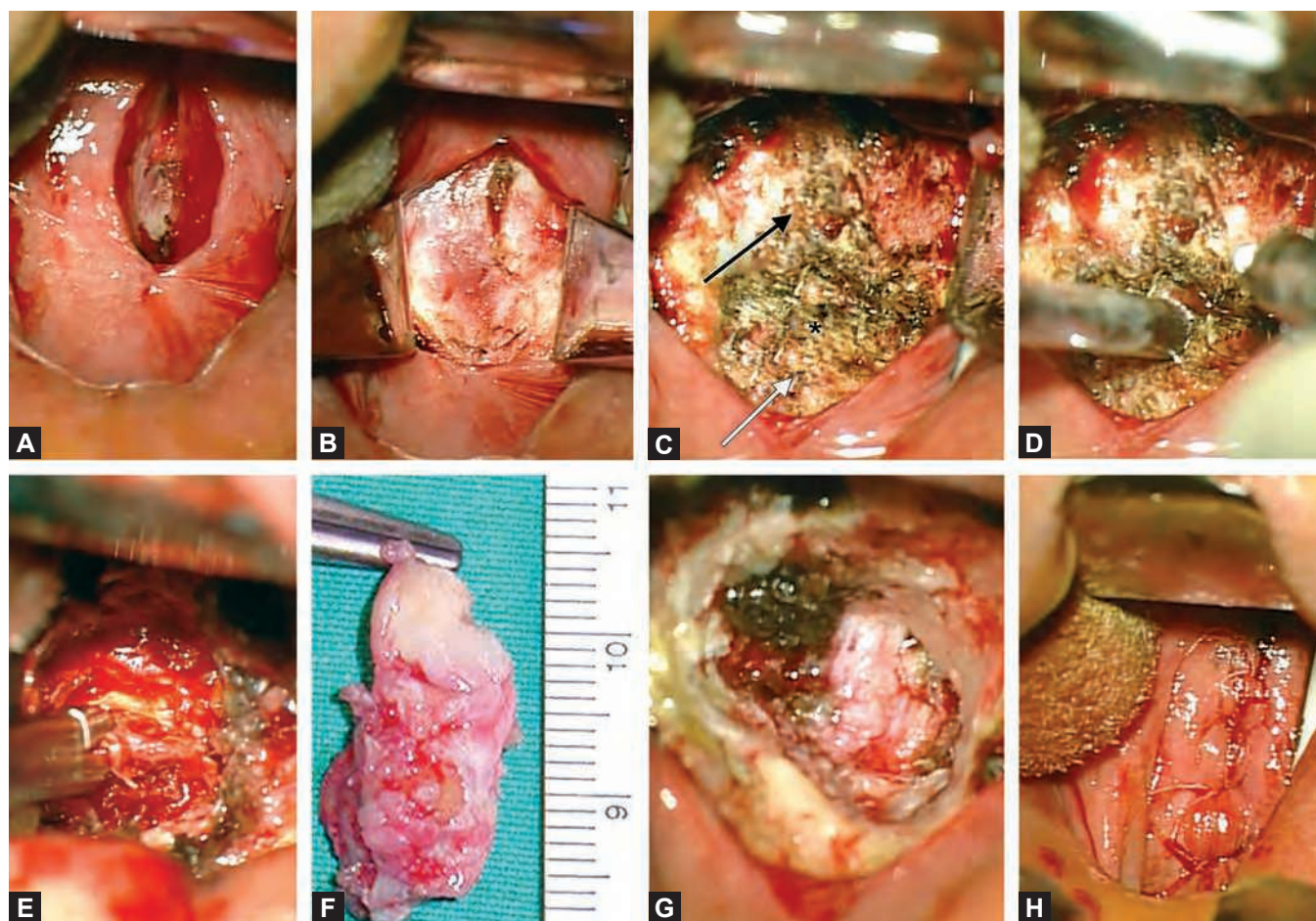
Several postoperative complications have been described after the TOA to CVJ.^{4,5,20–22} However, after an adequate learning curve and adopting some technical nuances, the occurrence of complications can be substantially reduced.

CSF Leakage and Meningitis

Cerebrospinal fluid (CSF) leakage due to inadvertent dural transgression can occur in the final stages of odontoid resection, especially in cases of severe basilar invagination.^{4,5,21} A CSF leak can lead to postoperative meningitis and should be treated aggressively when encountered. When the dura is clearly lacerated intraoperatively, primary dural repair should be attempted. The use of adipose tissue, fascia, and fibrin glue can be employed to enhance dural closure. In addition, placement of a lumbar subarachnoid drain is required at the end of the procedure.

Wound Dehiscence and Sepsis

Infection was initially considered a serious drawback to this operation because this approach is through a contaminated field. However, when the transoral procedure is used for extradural lesions of CVJ, the risk of postoperative infection is substantially lower. It has been suggested that the local resistance of the oral tissue to its own bacterial flora facilitates wound healing. Given the risk of



Figs. 47.6A to H: Intraoperative photographs of the patient presented in Figure 47.1. The tongue is oriented at the top of the photographs while the clivus is at the bottom. (A) A midline incision is made through the posterior pharyngeal wall in the median raphe. (B) The longus colli muscles are exposed and dissected with monopolar cauterization. (C) The anterior surfaces of the C1 arch (asterisk), the C2 vertebral body (black arrow), and the lower clivus (white arrow) are clearly identified. (D) The base of the dens and the inferior rim of the anterior arch of C1 are removed with a high-speed drill. (E and F) Transecting the base of the dens, the odontoid can be grasped with an odontoid rongeur, pulled inferoanteriorly and removed en bloc. (G) The decompression ends when the pulsating dura mater protrudes into the surgical field. (H) The mucosa and pharyngeal muscles are closed in a single layer.

wound dehiscence, the oral cavity should be periodically checked during the first week after the operation. A strict midline approach, judicious use of monopolar cautery, and a meticulous pharyngeal closure all reduce the occurrence of wound dehiscence. In the case of wound dehiscence, which generally occurs at the ends of the suture, the pharyngeal wound should be revised under general anesthesia.^{5,21}

Rhinolalia and Nasal Regurgitation

Incision of the soft palate with resultant fibrosis can lead to significant oropharyngeal morbidity, which ranges from velopharyngeal insufficiency to wound dehiscence

of the soft palate.²¹ In addition, an increased pharyngeal dead space as result of extensive bone removal at the CVJ promotes the poor apposition of the soft palate and nasopharynx, exacerbating velopharyngeal dysfunction. The occurrence of rhinolalia aperta and nasal regurgitation is significant functional deficit due to defects in the structure of the oropharynx and can be reduced by retracting, instead of cutting, the soft palate.

POSTOPERATIVE INSTABILITY

The TOA involves a significant osteoligamentous resection at the CVJ and predisposes to instability of this region. The risk of creating CVJ instability with TOAs to malformations

of CVJ has not been fully elucidated. Dickman et al.²³ in a retrospective analysis found that 40% of patients with fixed congenital osseous malformations exhibited C1–C2 instability after transoral surgery and required posterior fusion. Interestingly, patients who required posterior decompression of a Chiari malformation were at risk for developing instability as well. In fact, no consistent diagnostic criterion is available to predict whether and/or when a transoral odontoidectomy will cause instability in patients with CVJ malformations. Nonetheless, due to the potential morbidity of postoperative instability of CVJ, most authors advocate posterior fusion after transoral decompression.^{5,20,21,24,25} Instability after transoral surgery can occur in acute or delayed setting.^{20,23,26,27} In our early experience with 25 CVJ malformations treated with TOA, we have reported one postoperative death from acute dislocation of the axis on the day before a planned posterior fixation.²⁰

In order to eliminate the risk of acute postoperative instability and to mobilize the patient as soon as possible, we have moved from performing a planned delayed posterior fixation as a secondary procedure, to a one-stage transoral decompression and posterior occipitocervical fixation. Based on biomechanical studies, the integrity of the C1-ring is critical to minimize the risk of delayed instability of CVJ.²⁶ When the C1-ring is transected, a horizontal separation of lateral masses can occur, causing cranial settling of the C2 vertebral body, with resultant compression of cervicomedullary segment and neurological deterioration.²⁷ It is our policy, when feasible, to use the bottom-up C1-sparing drilling technique, in order to prevent the postoperative spreading of the C1-ring.

Several posterior systems of malleable rods with segmental wire fixation have been described in the literature, including Luque rectangle fixed at the upper cervical and occipital regions with steel wires, Hartshill-Ransford loop, threaded Steinmann pin, and Cotrel-Dubusset set. Wiring of the occiput may result in loss of vertical height due to telescoping of the implant. In addition, sublaminar wire passage can be dangerous for the spinal canal content. Occipital hook fixation has also been described, but has not widely adopted by spinal surgeons. Biomechanical studies have found that screw fixation of the occiput to the cervical spine provides the highest level of construct stiffness and is capable of resisting cranial settling and the geometrical loads applied at the CVJ.^{28,29} According to these findings, we favor the use of precontoured plate rod systems with bicortical screws in the occipital bone, C2 pedicles (when feasible), and lateral masses of the subaxial cervical spine.



Figs. 47.7A and B: (A) Midsagittal T2-weighted magnetic resonance imaging of the cervical spine, disclosing severe fixed posterior compression of the cervicomedullary junction. This 33-year-old woman complained of paresthesias in the limbs with attempted head extension. (B) Axial computed tomography slide confirms the posterior encroachment of the neuraxis by the abnormal lip of the foramen magnum.

Only local autologous bone and/or strips of iliac crest autograft are placed from the occiput to the posterior arch of C1 and to the laminae and lateral masses of the upper subaxial cervical vertebrae to promote solid fusion.

■ FORAMEN MAGNUM DECOMPRESSION

Isolated FMD is rarely indicated in patients with CVJ malformations. The main indication of this posterior approach is the occurrence of fixed posterior compression, which is an unusual finding (Figs. 47.7A and B).¹¹ In addition, isolated FMD should be considered in patients with basilar invagination due to horizontal angulation and shortening of the clivus associated with tonsillar prolapse, without significant ventral brainstem compression (Fig. 47.8).⁵ Finally, in patients with tonsillar prolapse and severe ventral compression in which the transoral decompression is not enough to ameliorate the overcrowding of the posterior cranial fossa, FMD should be performed in the same stage of occipitocervical fixation (Figs. 47.9A to F).⁵ In these patients, we perform an extra-arachnoidal osteodural craniocervical decompression directed toward decompressing cerebellar tonsils at the craniocervical junction and restoring CSF dynamics to normal.^{30,31}

Incision and Soft-Tissue Dissection

The patient's head is placed within the Mayfield head holder in a neutral position. A midline linear skin incision is

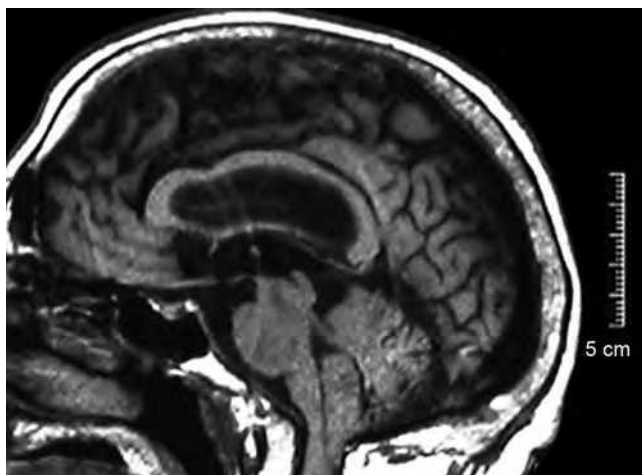
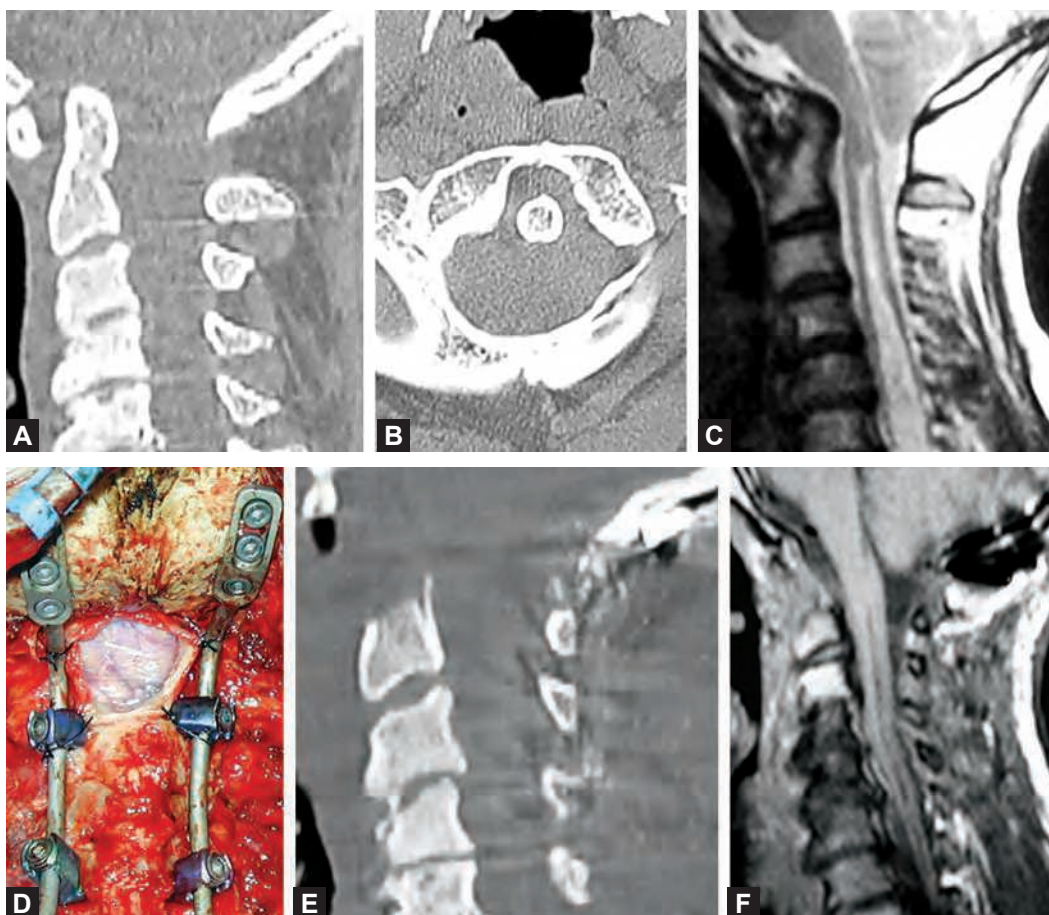


Fig. 47.8: Midsagittal T1-weighted magnetic resonance imaging scan disclosing tonsillar prolapse associated with shortening of the clivus, platybasia, and slight basilar invagination without significant ventral compression of the cervicomedullary junction. In this context, isolated posterior foramen magnum decompression should be considered.



Figs. 47.9A to F: (A) Preoperative sagittally reformatted and axial (B) computed tomography slides of a 47-year-old woman, disclosing basilar invagination and atlantoaxial dislocation. (C) Preoperative midsagittal T2-weighted magnetic resonance imaging (MRI) scan disclosing tonsillar herniation and cervical syringomyelia. The patient underwent single-stage anterior decompression and posterior craniocervical decompression with occipitocervical fixation. (D) Intraoperative photograph after extra-arachnoidal craniocervical decompression and fixation were performed. (E) Postoperative sagittally reformatted computed tomography scan demonstrating removal of the odontoid with sparing of the anterior ring of the atlas. (F) Postoperative midsagittal T1-weighted MRI scan obtained at 6 months, showing ascent of the cerebellar tonsils and shrinkage of the syrinx.

planned from just the inion to the second or third cervical spine, depending on the extent of cerebellar herniation. A subperiosteal dissection of the squamous part of the occipital bone and the posterior arch of C1 is performed. The subperiosteal dissection of the spinous process and lamina of C2 is done only when a C2 laminectomy is planned. After the subperiosteal dissection, the convex external surface of the squamous part of the occipital bone with its bony prominences (i.e. inion, superior and inferior nuchal lines, external occipital crest) and the posterior aspects of C1 and C2 (when necessary) are exposed.

Bone Removal

The suboccipital region below the inferior nuchal line is carefully decompressed by removal of the posterior lip of the foramen magnum, typically very thick, using the high-speed drill with a cutting burr and a Kerrison rongeur. Once the suboccipital bone decompression is completed, a small craniectomy approximately 2.5 cm in width and 2 cm upward from the edge of the foramen magnum can be observed. At this point, the posterior arch of C1 and, when necessary, the lamina and the spinous process of C2 are removed.

Dural Decompression

The dural surface of the craniocervical junction is carefully examined under the operative microscope, and a band of thickened tissue on the outer surface of the dura can be observed at the craniospinal level. This fibrous band is removed and the dura is then opened in a linear fashion using a No. 11 blade. After a small opening in the dura is made, we favor the use of a cervical body dissector to tent up and to progressively cut the dura above it using the blade. Careful attention is given to ensure the underlying arachnoid remains intact. At this point, the free CSF flow is observed beneath the transparent and intact arachnoid at the craniospinal level and confirms the decompression of the cerebellar tonsils. At the end of the osteodural decompression, the tonsillar tips should be clearly seen free within the new spacious cisterna magna. The dura is then stitched laterally to the muscles using a 2-0 silk suture and is left open. In patients with arachnoid changes suggesting adhesive arachnoiditis, the arachnoid should be dissected to restore CSF pathways along with the craniocervical decompression and duraplasty.

It has been widely reported in the literature that the main factor affecting the occurrence of cerebellar ptosis after FMD is a too large of a suboccipital craniectomy for the specific patient.³² In our experience, a conservative “craniectomy” is adequate to decompress the craniocervical junction in patients with overcrowding of the posterior cranial fossa and does not interfere with the occipitocervical fixation.

KEY POINTS

- The TOA is the most effective route for the treatment of the bony abnormalities that exert irreducible ventral compression of the cervicomedullary junction.
- Transmaxillary approaches are adjuncts to the TOA in patients with severe basilar invagination and limited jaw mobility.
- Transoral decompression is effective in inducing syrinx shrinkage in most patients with basilar invagination and tonsillar prolapse.
- The high risk of postoperative craniocervical instability after transoral decompression mandates posterior fixation and fusion in the same surgical session.
- Posterior craniocervical decompression is rarely required in patients with irreducible bony ventral compression of the cervicomedullary junction.

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- Transoral approach represents the standard approach for the treatment of irreducible anterior abnormalities that compress the cervicomedullary junction. Its superior extensions (transmaxillary approaches) are required in a small subset of patients with severe basilar invagination (LeFort I Osteotomy) and small interdental space (open-door maxillotomy approach).
- Menezes AH, VanGilder JC, Graf CJ, et al. Craniocervical abnormalities. A comprehensive surgical approach. *J Neurosurg*. 1980;53:444-55.
- Craniocervical abnormalities should be preoperatively evaluated with a physiological approach. Stabilization and

fusion are the goal in the treatment of reducible lesions, whereas decompression of cervicomedullary junction is the standard treatment in irreducible cases. Transoral decompression is indicated in cases of ventral compression, posterior decompression is the treatment when bone impingement is present from the dorsal aspect.

Menezes AH. Craniovertebral junction abnormalities with hindbrain herniation and syringomyelia: regression of syringomyelia after removal of ventral craniovertebral junction compression. *J Neurosurg.* 2012;116:301-9. Patients with ventral symptomatic craniovertebral junction abnormalities have 33-38% incidence of hindbrain abnormalities. These patients can develop early or delayed neurological deterioration after primary posterior fossa decompression. Transoral decompression in irreducible pathology can allow for regression of the syrinx and patient improvement.

Dickman CA, Locantore J, Fessler RG. The influence of odontoid resection on stability of the craniovertebral junction. *J Neurosurg.* 1992;77:525-30.

Transoral decompression can exacerbate pre-existing craniocervical instability or induce pathological instability. The factors affecting the occurrence of postoperative instability are the extent of pathological bone destruction, ligamentous weakening, and operative bone removal.

Naderi S, Crawford NR, Melton MS, et al. Biomechanical analysis of cranial settling after transoral odontoidectomy. *Neurosurg Focus.* 1999;6(6).

The integrity of C1 ring has shown to be decisive in maintaining normal occiput-C2 separation. Transection of the ring of C1 during transoral approach can induce horizontal separation of lateral masses, causing cranial settling of C2 vertebral body with resultant cervicomedullary compression.

Kyphotic Cervical Deformity Correction Including Post-traumatic and Post-laminectomy Kyphosis

Lyle C Young, John M Rhee

Snapshot

- » Biomechanics and Etiology
- » Clinical Presentation
- » Incidence and Epidemiology
- » Post-traumatic Kyphosis
- » Surgical Strategies for Correction
- » Outcomes of Surgery

BIOMECHANICS AND ETIOLOGY

The normal cervical weight-bearing axis in the sagittal plane begins at the occipital condyles and should fall posterior to the vertebrae of C2–C7, passing through the middle of the C1 and T1 bodies.¹ While the exact amount of normal lordosis is somewhat challenging to define in vivo, various authors have suggested ranges between 16° and 25° in asymptomatic patients.² There are multiple methods of measuring cervical lordosis. Common methods include (1) the C2–C7 Cobb angle or (2) cervical sagittal vertical axis, the distance from the C2 plumb line to the posterior C7–T1 vertebral bodies. Normal cervical lordosis exists due to multiple structures, chief among these are the vertebral bodies and intervertebral disks. The bodies exhibit increasing size moving from a cephalad to caudal direction and the intervertebral disks, which comprise 15% of overall cervical height, have a larger anterior than posterior height. A proper sagittal vertical axis helps maintain a lordotic alignment to the cervical spine, and places 36% of loads through the anterior column versus 64% through the dorsal spinal column.³ Thus, the biomechanical demands on the posterior neck musculature are reduced and balanced by the favorable alignment that exists in the normal cervical spine.

Dorsal structures in the cervical spine have been recognized to be integral in maintaining normal lordotic posture. Among these are the cervical lamina, interspinous ligaments, facet joint capsules, and ligamentum flavum. A cervical laminectomy in the absence of fusion of a flexible spine leads to kyphosis by deranging this biomechanical balance in several ways. First, the surgical approach involves a dissection of the cervical extensor musculature, which can lead to denervation, fibrosis, or atrophy, making the muscles less capable of performing their normal duties. The muscles can be placed at further disadvantage if the attachments of the semispinalis cervicis and capitis, the primary extensor muscles of the neck and head, have been disrupted off C2. Second, a cervical laminectomy involves the removal of some of the posterior soft-tissue restraints that can act as a tension band, such as the supraspinous ligament, interspinous ligament, ligamentum flavum, and facet capsules. Third, overaggressive facet resection can lead to instability and kyphosis. Cadaveric sectioning studies have demonstrated that instability is prone to develop when >50% of a facet joint has been removed. The postlaminectomy kyphosis that occurs in the setting of aggressive facetectomy may be particularly

severe due to the combination of kyphosis and spondylolisthesis that arises and is exacerbated by compromising the normal compressive force seen by the facet joints in the cervical spine.³

This unfavorable biomechanical environment then leads to a situation in which “kyphosis begets kyphosis.”⁴ As the head translates anteriorly, the sagittal vertical axis moves anteriorly, causing additional compressive loads on the anterior column and tensile loads on the posterior column, which it is less capable of withstanding. This further compromises the mechanical disadvantage introduced by laminectomy on the posterior extensor muscles. The posterior ligamentous restraints are then also put under further tension, additionally limiting their ability to act as tension bands. Further, as the posterior musculature is elongated, there is less sarcomere overlap and the muscles become subjected to increasingly unfavorable ranges in their length–tension curves, further decreasing their action. As a result of the kyphotic deformity, the spinal cord may be draped over the kyphosis and lead to impairment in spinal cord vascularity as well as mechanical compression arising from the anterior vertebral bodies. Posterior compression of the spinal cord may also result from postlaminectomy kyphosis due to the formation of postlaminectomy membranes that can compress the dura in extension.⁵ Because of this well-studied biomechanical cycle, it is crucial to avoid performing a stand-alone laminectomy without fusion if the cervical spine already demonstrates loss of lordosis preoperatively, as the posterior anatomic structures in this scenario begin at a disadvantage and are almost certain to further deteriorate after laminectomy.

CLINICAL PRESENTATION

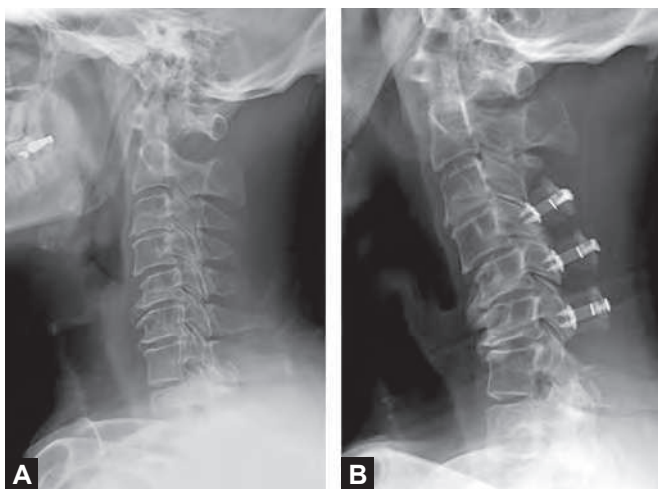
Many who go on to develop postlaminectomy kyphosis have initial improvement in their presenting neurologic symptoms from the decompressive operation. However, as the deforming forces progress and kyphosis develops, they may present with a variety of possible complaints. Chief among these are axial neck pain, muscular fatigue and spasm. Typically, these symptoms are mechanical and demonstrate a reasonable degree of relief at rest. As the deformity progresses beyond the elastic limitations of the spinal cord or nerve roots, myelopathy and/or radiculopathy can recur. Although the resultant foraminal narrowing may lead to presenting complaints of radiculopathy, treating surgeons should nevertheless maintain a high index of suspicion for subtle evidence of myelopathy. In the most

severe situations, kyphosis can lead to loss of forward gaze, difficulty swallowing and eating, poor hygiene in the anterior neck, and the need to prop up the neck with the hands. Respiratory problems and dysphagia are rare but reported symptoms in the more severe cases.

INCIDENCE AND EPIDEMIOLOGY

While the true incidence of postlaminectomy kyphosis is unclear, it appears to be more common in children than adults. The reported incidence of postlaminectomy kyphosis varies widely. Mikawa reported that 52% of patients demonstrated change in cervical alignment after multilevel laminectomy, with 14% developing kyphosis.⁴ Guigui noted that 31% had a change in alignment versus preoperative, with 25% having increased kyphosis.⁶ Pediatric rates of postlaminectomy kyphosis are thought to be higher due to the effects of residual growth potential in the setting of deranged force balance from the disrupted posterior stabilizing structures, negative effects of radiation therapy given to children who undergo laminectomy for tumors, the theoretically increased laxity in pediatric supporting structures, or the relative lack of spondylosis and stabilizing osteophytes in children compared with adults.⁷

Risk factors for the development of postlaminectomy kyphosis include pre-existing lack of lordosis, younger age at time of surgery, number of levels removed, especially four or more levels, laminectomized surgery involving the C2 lamina, performance of facetectomies, presence of intraspinal tumors, irradiation, and increased preoperative range of motion.^{6,8} Although laminoplasty was initially designed in order to prevent the development of postlaminectomy kyphosis, some loss of lordosis also occurs with laminoplasty. In general, however, the loss of lordosis after laminoplasty tends to be less than that seen after laminectomy and, much less commonly, of clinical significance in the properly chosen patient (Figs. 48.1A and B). Suk reported on average 5° loss of lordosis after laminoplasty, with 10.6% of patients developing an average of 12° of kyphosis. As one would predict, those who began with less lordosis (<10° preoperative) were more likely to develop kyphosis, as were those demonstrating more global flexion than extension on preoperative dynamic radiographs.⁹ Loss of lordosis with laminoplasty may be lessened by sparing C2. Takeshita found that the decrease in lordosis from C2 to C7 was 8.3° if C2 was split during laminoplasty, 5.2° with a dome-like laminotomy of C2, but only 1.5° if C2 was left completely intact.¹⁰



Figs. 48.1A and B: Postlaminoplasty K. (A) Preoperative and (B) postoperative X-rays of postlaminoplasty kyphosis. Some loss of lordosis is common after laminoplasty. Although the magnitude is generally not as severe as that seen after multilevel laminectomy, kyphosis can develop after laminoplasty as well.

The importance of preserving the attachments to C7 appears to be much less significant: Kowatari found no change in axial neck pain, Japanese Orthopaedic Association Scores, or final sagittal alignment whether the C7 attachments were preserved or not.¹¹

POST-TRAUMATIC KYPHOSIS

While the various causes of acquired cervical kyphosis are myriad and can include trauma, neoplasm, surgery, congenital deformities, skeletal dysplasias, degenerative joint disease, inflammatory conditions, and neuromuscular disorders, relatively little has been studied on post-traumatic kyphosis as a clinical entity. Post-traumatic kyphosis can arise from an injury that was either missed or incompletely treated. Additionally, pre-existing host factors may predispose a patient to development of post-traumatic kyphosis even in the setting of an otherwise innocuous-appearing injury.

Injuries that predispose to the development of post-traumatic kyphosis can be broadly grouped into anterior and posterior injuries. Vertebral body loss of height after a fracture can create tensile forces at the posterior stabilizing structures of the neck and lead to post-traumatic kyphosis. Likewise, a dorsal injury such as to the ligamentous structures or facet fracture may compromise the compressive integrity of the posterior tension band. Regardless of the

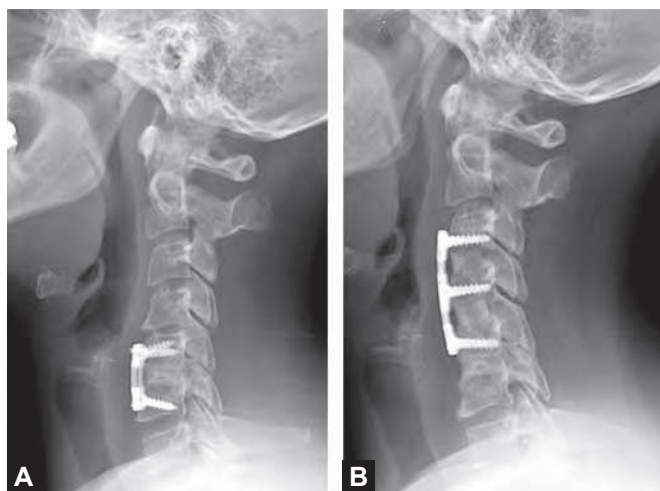
initiating event, the final common pathway of post-traumatic kyphosis results in the head and the overall weight-bearing axis shifting anteriorly.

While it has been posited that the most common traumatic injury for the development of post-traumatic kyphosis is the occult or underappreciated ligamentous injury,¹² of the well-recognized mechanisms, flexion-distraction and the so-called tear-drop (flexion-compression) injury patterns based on the Allen-Ferguson classification are the most likely to result in the development of post-traumatic kyphosis. Prompt recognition of these injuries and a properly planned treatment strategy is essential in avoiding potentially problematic kyphotic sequelae. Often times these sequelae may require multistage surgical approaches to correct.

Recent advances in spinal instrumentation combined with more broad application of screening cervical computed tomography (CT) scans in the setting of trauma are thought to have decreased the rates of inadequately treated and/or unappreciated injuries. While CT scanning as the primary radiographic tool in many trauma centers has all but supplanted plain radiography, it does not necessarily detect ligamentous injuries. Nevertheless, it is helpful in showing soft-tissue swelling and fluid that may prompt further investigation. Magnetic resonance imaging has become the gold standard in detecting posterior ligamentous injuries to the cervical spine. In addition, serial standing lateral cervical X-rays can help a clinician detect delayed post-traumatic kyphosis. Decreasing use of external orthotics such as halo vests to treat potentially unstable cervical injuries in favor of rigid segmental implants has also played a role in declining rates of post-traumatic kyphosis. Fisher et al. reported a series of 45 patients with unstable flexion-compression cervical fractures treated either with HALO vest or anterior corpectomy and plating and found a 20% rate of failure for the group treated with HALO immobilization.¹³

SURGICAL STRATEGIES FOR CORRECTION

Significant pain as well as functional and neurologic impairment can all be presenting hallmarks of post-laminectomy kyphosis. Nonoperative treatments such as physical therapy for extensor muscle strengthening may be sufficient in mild cases of kyphosis, but is unlikely to be of major benefit in those with significant, progressive



Figs. 48.2A and B: Anterior only. (A) This patient had undergone an initial ACDF at C56 and then a multilevel laminectomy. She presented with recurrent myelopathy and a mild postlaminectomy kyphosis, with cord compression at C34 and C45. (B) Status post-removal of plate at C56 and then anterior-only surgery at C34 and C45 for spinal cord decompression.

kyphosis and should not be considered a mainstay of treatment. In symptomatic patients with significant kyphosis, a surgical approach is generally required, particularly if there is myelopathy. Goals of treatment include (1) correction and fusion of deformity, ideally with a normalized sagittal vertical axis; (2) neurologic decompression; and (3) pain relief.

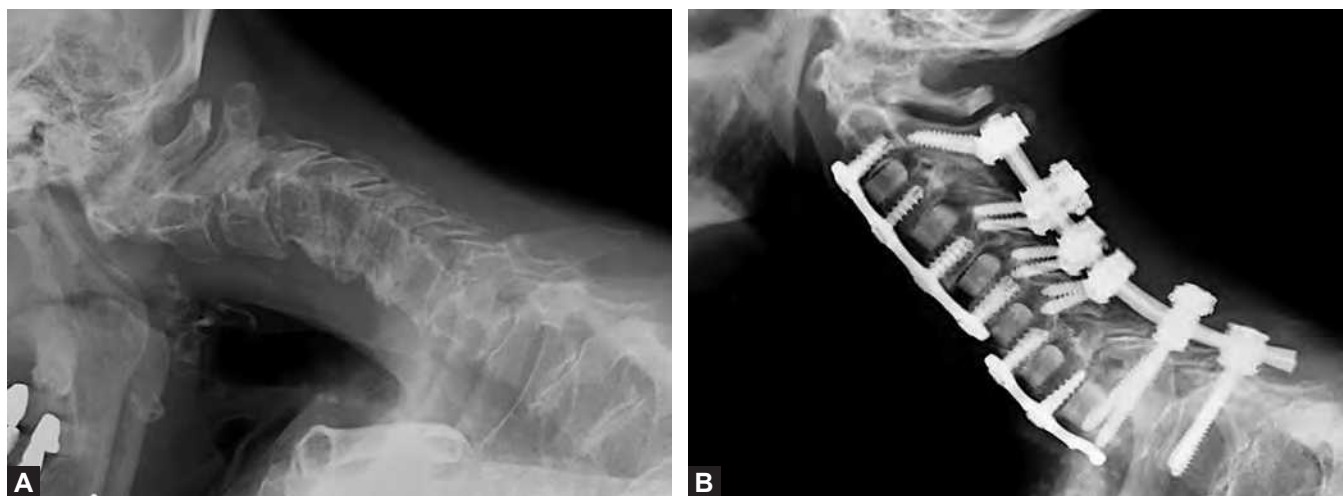
Flexible and Passively Correctable Kyphosis

If the deformity is flexible and passively correctable, then it may be reduced into the desired alignment and fused either anteriorly or posteriorly. The flexibility of a deformity can be ascertained from the supine CT sagittal scan with a bump placed under the patients' shoulders to induce maximal extension. Anterior-only surgery has several advantages. Anterior surgery can allow for the direct decompression of a spinal cord draped over a kyphos, avoids reoperation through a revision approach posteriorly, preserves the posterior musculature that has already been compromised, and provides height restoration to the anterior column through the use of structural interbody or corpectomy grafts (Figs. 48.2A and B). However, disadvantages of anterior only surgery include relatively less biomechanically secure fixation in the vertebral bodies versus the dorsal

elements (especially relevant in osteopenic patients) and the inability of anterior plates to restore the posterior tension band. Although anterior plates may "hold" the correction achieved through the placement of interbody grafts, they are at a relative mechanical disadvantage secondary to their action being by definition anterior to the axis of rotation of the kyphotic deformity.

Reduction in a kyphotic deformity can be performed using an anterior plate and screws after multilevel anterior interbody grafts are placed. This technique can be very powerful in correcting kyphosis. The lordotic anterior plate should be loosely secured to the proximal and distal levels. Screws can then be placed into the middle levels using the plate and screws to draw the vertebral bodies anteriorly toward the plate. The proximal and distal levels are then secured and finally tightened after the middle segments have been lagged up toward the plate. Depending on the bone quality, we generally advocate supplemental posterior fixation particularly when the anterior operation includes more than three segments.

Posterior-only surgery can also be considered in the scenario of a flexible and passively correctable kyphosis. However, in this case, it is mandatory that sufficient spinal cord decompression can be achieved through realignment and restoration of lordosis in those with neurologic compression. If this is deemed not possible, alternative strategies must be employed to achieve realignment. Posterior surgery has the advantage of generally superior fixation versus anterior plates, particularly at the ends of the construct, where pedicle screws can be routinely placed into C2, C7, and the upper thoracic spine. In addition, posterior implants are at a mechanical advantage in correcting kyphosis in that they act posterior to the axis of rotation of the kyphotic deformity. Disadvantages to posterior-only based surgery include the need for a revision approach through scar with no dural protection due to previous laminectomy, further denervation and damage to the already-compromised posterior musculature, more perioperative pain than is encountered with an anterior approach, higher wound infection rates, and limited surface areas for bone grafting and fusion. Furthermore, the lack of anterior column load sharing may make posterior constructs more prone to implant failure and screw pullout—especially at the proximal end of the construct—if the fixation is not optimal and the neck settles back toward its original kyphotic state. This is an especially important consideration in the osteopenic patient.



Figs. 48.3A and B: Anterior-posterior. (A) Elderly woman status post multilevel laminectomy who developed severe postlaminectomy kyphosis and myelopathy. (B) Due to the rigid, multilevel deformity and suspected osteopenia, a combined anterior-posterior operation was performed from C2 to T2.

Although anterior- or posterior-only surgery can generally be utilized in those with flexible deformities, other factors should be taken into consideration. In those with poor bone quality or who need a long segment fusion, an anterior approach alone may be insufficient as the screw fixation achieved in the vertebral bodies via anterior cervical plates may not be enough to counteract the deforming forces. In such cases, significant pistoning of the interbody grafts into soft endplates may occur as the spine settles back into its original kyphotic alignment. Furthermore, if a multilevel corpectomy is needed for neurologic decompression in the setting of postlaminectomy kyphosis, high rates of failure can be anticipated with anterior-only surgery due to the severe instability that develops from disconnecting the two sides of the spine with the corpectomy anteriorly and the laminectomy posteriorly.¹⁴ If bone quality is adequate and the goals of surgery can be accomplished with discectomies or short segment combination corpectomy-discectomy rather than long corpectomies, anterior-only surgery may be adequate. Should these factors not be met, a combined anterior-posterior approach is more likely to result in favorable outcomes. In addition, in cases in which the sagittal vertical axis cannot be restored, consideration should be given to maximal fixation, since major deforming forces will still be present. It is our preference to extend the fusion in to the proximal thoracic spine with pedicular screw fixation to prevent distal junctional kyphosis in the setting of postlaminectomy kyphosis.

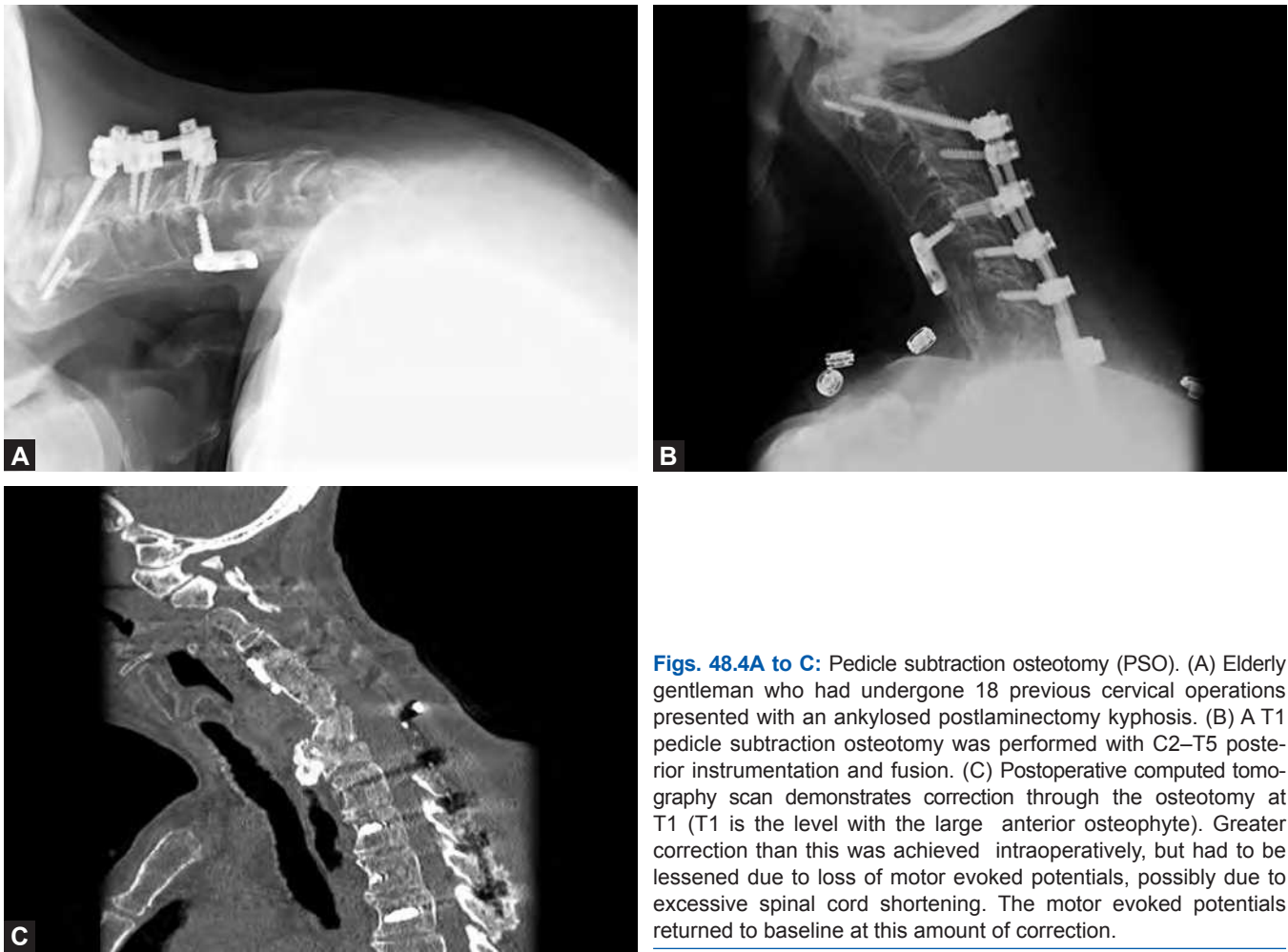
Fixed (Nonflexible) but Nonankylosed Postlaminectomy Kyphosis

If the deformity is fixed but not fused, anterior-only or combined anterior release and correction followed by posterior fusion may be appropriate depending on patient bone quality and severity of kyphosis (Figs. 48.3A and B). Again, a combined approach is best if multilevel anterior corpectomies are needed, whereas an anterior-only approach may suffice if multilevel discectomies with segmental screw-plate fixation can be performed in a patient with adequate bone quality. Inability to restore the sagittal vertical axis makes loss of correction more likely due to persistence of deforming forces, and supplemental posterior fixation should be strongly considered.

Fixed and Ankylosed Postlaminectomy Kyphosis

If the deformity is not only fixed but also fused (based on CT), then osteotomies may be required in order to achieve satisfactory correction. Osteotomies are necessary when the ankylosed segments are in such severe kyphosis that correction through the adjacent segments alone would not provide sufficient overall restoration of the sagittal vertical axis (Figs. 48.4A to C).

The approach and order of addressing the kyphosis are dictated by the location of the ankylosis. If the ankylosis is posterior, then a posterior approach should be performed first in order to osteotomize the area of ankylosis. Correc-



Figs. 48.4A to C: Pedicle subtraction osteotomy (PSO). (A) Elderly gentleman who had undergone 18 previous cervical operations presented with an ankylosed postlaminectomy kyphosis. (B) A T1 pedicle subtraction osteotomy was performed with C2–T5 posterior instrumentation and fusion. (C) Postoperative computed tomography scan demonstrates correction through the osteotomy at T1 (T1 is the level with the large anterior osteophyte). Greater correction than this was achieved intraoperatively, but had to be lessened due to loss of motor evoked potentials, possibly due to excessive spinal cord shortening. The motor evoked potentials returned to baseline at this amount of correction.

tion is obtained through the osteotomy, but supplemental anterior release and interbody grafting are often needed, followed by a second posterior approach to lock in the instrumentation (“back-front-back”). In the case of anteriorly based ankylosis, an anterior osteotomy is performed first. Should sufficient correction be achieved and bone quality be present, anterior-only surgery may be performed in this setting. Otherwise, a supplemental posterior approach is performed in order to augment the anterior correction. In patients demonstrating circumferential ankylosis, posterior osteotomies and establishment of fixation points, followed by anterior osteotomies and interbody grafting, followed by final posterior rod fixation and fusion will likely provide the best correction and final clinical result.

OUTCOMES OF SURGERY

Although the surgical management of postlaminectomy kyphosis can be challenging, high rates of successful

outcomes have been reported. Steinmetz et al. examined 10 patients treated with anterior-only correction of postlaminectomy kyphosis. The mean preoperative kyphosis measured $+13^\circ$ and was corrected to -6° of lordosis postoperatively.¹⁵ No failures were noted in this series, and loss of correction averaged only 2° at 6-month follow-up. Complications involved two cases of persistent hoarseness and one case of transient dysphagia lasting <6 months. However, the overall magnitude of kyphosis in this series was not severe. Another series evaluated patients with overall greater degrees of kyphosis who underwent anterior and posterior surgery.¹⁶ The average preoperative kyphosis was $+38^\circ$ and improved to -10° of lordosis at final follow-up. No implant failures were reported, although one patient required late revision for caudal progression of deformity. Two patients had durotomies, three had transient C5 root palsies, and another patient sustained quad-

riplegia from failure of the head-holding device. Abumi reported on the use of subaxial cervical pedicle screws in 17 patients who underwent posterior only surgery and 13 who had combined anterior and posterior surgery.¹⁷ At minimum 2-year follow-up, kyphosis improved from +28° to +5° in those with posterior-only surgery with subaxial pedicle screws, and from +31° to +0.5° in those with combined procedures also utilizing subaxial pedicle screws. Solid fusion was achieved in all patients. One patient had a pedicle fracture with root irritation that required screw removal, and another had symptomatic foraminal stenosis caused by reduction in anterior translation that required foraminotomy. No spinal cord or vertebral artery injuries occurred in this series.

CONCLUSION

The mainstay of treatment of postlaminectomy kyphosis should be prevention. As such, there are currently very limited indications for performing laminectomy alone when treating multilevel cervical myelopathy. Rather, laminoplasty or laminectomy with fusion should be considered in the majority of patients who require multilevel posterior cervical surgery as an index operation. In those who do develop symptomatic postlaminectomy kyphosis, a surgical approach is often required, particularly for those with associated myelopathy. For mild, flexible deformities, anterior surgery may be best because it allows for direct neurologic decompression, avoids a revision posterior approach, creates less perioperative pain, and recreates anterior column height. However, those with severe deformities, particularly in the setting of osteopenia, should generally undergo both anterior and posterior surgery, as the mechanical demands may exceed those provided by anterior implants alone. The exact sequence of anterior and posterior approaches will depend on the nature of the deformity, as well as the presence of associated bony ankylosis. The more severe the kyphosis, the better and more extensive the fixation should be in order to avoid complications related to implant failure. This is particularly true for patients in whom restoration of the sagittal vertical axis is either not practical or not obtained, as the presence of any residual kyphosis places great demands on the instrumentation and bone-implant interfaces. In order to prevent spinal cord injury, one should generally avoid placing tensile forces on the spinal cord by first achieving thorough decompression prior to the application

of corrective forces, and then reconstruct the spine so as to lengthen the anterior column while shortening the posterior column. With proper planning and surgical technique, the literature demonstrates that successful outcomes can be achieved.

KEY POINTS

- Normal cervical lordosis (Cobb angle from C2 to C7) ranges between 16° and 25° and is key in maintaining a proper biomechanical homeostasis in the cervical spine. Dorsal and ventral structures act to maintain cervical lordosis.
- Postlaminectomy kyphosis can present insidiously with vague complaints such as axial neck pain, muscle fatigue and spasm, radiculopathy, and myelopathy. Late findings can include loss of forward gaze, difficulty swallowing, and even respiratory problems.
- Risk factors for postlaminectomy kyphosis include pre-existing lack of lordosis, younger age at time of surgery, number of levels removed, involvement of the C2 lamina, and irradiation.
- Post-traumatic kyphosis can occur in the setting of subtle or occult ligamentous injury. Improvements in fixation techniques and implants, decreasing of external orthoses, and wider availability of CT scanning for trauma have all been thought to decrease the rates of post-traumatic kyphosis.
- Goals of treatment in postlaminectomy and post-traumatic kyphosis include correction and fusion of deformity, neurologic decompression, and relief of pain.

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Osteotomies in the Cervical Spine

Hossein Elgafy, Erik Peterson

Snapshot

- » Cervical Kyphosis
- » Preoperative Considerations and Evaluation
- » Osteotomy Options
- » Postoperative Management
- » Outcomes
- » Complications
- » Authors' Preferred Method, Avoiding Pitfalls, and Complications

CERVICAL KYPHOSIS

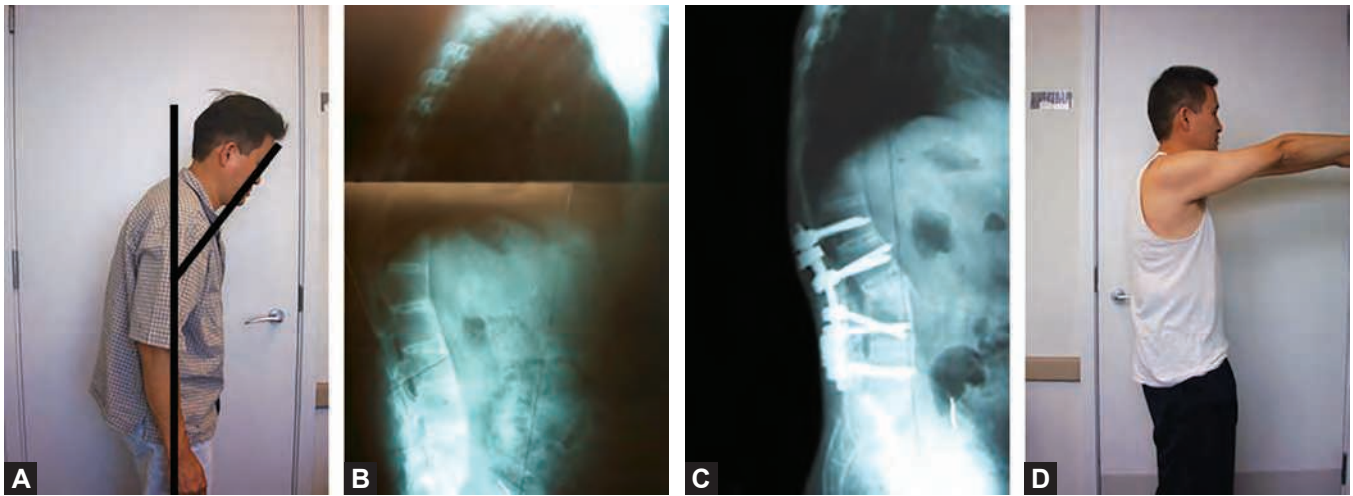
The severely kyphotic and fixed cervical spine poses a challenge to patients and spine surgeons alike. Patients complain of progressive deformity of the cervical spine, causing both axial neck and radicular pain. As the deformity progresses, they are left unable to chew, swallow, perform hygiene or raise their eyes to see ahead of their feet—the so-called “loss of forward gaze” or “chin-on-chest” deformity, in the severe form.

The etiology of cervical kyphosis is varied. Most frequently it arises from progressive deformity from the spondyloarthropathies, most commonly ankylosing spondylitis (AS). It may also come from malunion of cervical spine fractures, degenerative spondylosis, postinfectious deformity, tumor, or from iatrogenic causes such as destabilization of the posterior elements after laminectomy. After the initial insult, the weight of the head is transferred anterior to its normal position, disrupting normal sagittal balance. With time, gravity pulls the weight of the head anterior, and bony remodeling, especially in the case of AS, leads to a progressive and fixed deformity. Although the deformity is still flexible, nonoperative therapy may involve simple modifications, such as avoidance of too many pillows to prevent loss of extension. For fixed deformities, there are limited nonoperative management options consisting mainly of activity modification, such as the avoidance of driving, to accommodate the loss of horizontal gaze in those with fixed deformity.

The aims of cervical osteotomy are to correct sagittal imbalance, reverse the kyphotic deformity, and restore the patient's horizontal gaze. Generally, osteotomy is undertaken at the cervicothoracic junction (CTJ) at the C7–T1 level, though correction can take place at any level of the cervical spine. The CTJ lends itself as the ideal location for osteotomy and correction for a number of reasons. First, the cervical spinal canal progressively widens from cephalad to caudad, becoming widest at C7–T1. This affords itself to posterior osteotomy, as the procedure requires extension of posterior elements, which can buckle the posterior dura, leading to stenosis and spinal cord injury. Second, 90% of the time, the vertebral artery (VA) enters the transverse foramen at the C6 level. Osteotomy caudad to this level removes the danger of injury to the VA during the osteotomy as the VA lays anteriorly. Finally, in the event of spinal cord injury during either osteotomy or extension of the osteotomized segments, injury should theoretically allow the patient to maintain use of upper extremities when compared to midcervical spinal cord injuries.

PREOPERATIVE CONSIDERATIONS AND EVALUATION

Patient selection is critical for success. Contraindications to cervical osteotomy include patients with flexible deformities and those with fixed deformities not severe enough



Figs. 49.1A to D: (A) A patient with ankylosing spondylitis presented with progressive loss of forward gaze with a chin–brow vertical angle of 30° . (B) Preoperative lateral upright radiograph shows global positive sagittal imbalance due to thoracic kyphosis with loss of lumbar lordosis. (C) Postoperative lateral upright radiograph after L3 pedicle subtraction osteotomy shows correction of the global sagittal imbalance. (D) Follow-up photograph shows improvement in the sagittal balance and forward gaze.

to warrant such a large undertaking. Flexible deformity can be treated with multilevel anterior or combined anterior/posterior procedures followed by segmental fixation. Many patients with cervical kyphosis have deformities in the lumbar and thoracic spine, as well as hip contractures that may be contributing to the sagittal imbalance and loss of horizontal gaze. A cervical kyphosis of $<30^\circ$ generally does not warrant cervical osteotomy correction; in such a patient, one has to assess the global sagittal imbalance and evaluate the lumbar spine and the hip joints for their contribution in the disability associated with sagittal imbalance. Correction of these deformities should be attempted before undertaking an osteotomy at the cervical spine. Deformity in the hips is generally addressed before lumbar or thoracic spine, and lumbar and thoracic deformities are corrected before the cervical spine (Figs. 49.1A to D).

Poor candidates include those unable to be positioned in the method of the surgeon's choice. Prone positioning may be problematic for patients with pulmonary limitations. Other relative contraindications include bleeding disorders, those medically unfit for surgery, and those unable to participate in postoperative rehabilitation.

As with any spine surgery, medical comorbidities should be optimized with the assistance of the appropriate medical specialists. Severe thoracic kyphosis may limit pulmonary function, and increase the risk for anesthesia and positioning in the prone position. History of trauma, infection, cancer, or previous surgery should be elicited. History should focus on limitations of deformity. Patients

unable to chew and swallow may be malnourished, which may require dietary optimization before surgical procedures to avoid pseudarthrosis and wound healing complications. Nonsteroidal anti-inflammatories should also be terminated to avoid risks of excessive bleeding and risks of delayed fusion. Detailed neurologic examination may demonstrate preexisting neurologic injury, including C8 nerve root and possible myelopathy, though this has been shown to be relatively uncommon in kyphotic deformity.

Clinical evaluation of the sagittal imbalance starts with examination of the patient while standing with knees and hips fully extended in order to eliminate any compensatory knee or hip flexion that may mask a severe deformity. The patient is then examined in the sitting position; if the trunk appears with good balance in relation to the pelvis, then hip flexion contracture may be the cause and this can be demonstrated with the Thomas test. If the forward displacement of C2 in relation to the pelvis remains in the sitting position, the patient is then assessed in the supine position. When the deformity is localized to the lumbar spine, patients will be able to lie with their shoulders on the table. If the head and upper thoracic spine remains elevated from the table, fixed deformity in the cervical and/or thoracic spine is likely.

Chin brow to vertical angle (CBVA) is measured in the standing position with knees and hips fully extended. This is best measured with photography (Figs. 49.1 and 49.2). A vertical line is drawn perpendicular to the ground. A separate line connects the chin to the brow. The intersection



Figs. 49.2A to D: (A) A patient with ankylosing spondylitis presented with chin-on-chest deformity and a chin-brow vertical angle of 86° . (B) Preoperative lateral upright radiograph shows cervical kyphosis. (C) Intraoperative lateral upright radiograph after C7–T1 posterior extension osteotomy shows correction of the cervical kyphosis. (D) Follow-up photograph shows improvement in the sagittal balance and forward gaze.

angle is the CBVA, and in the normal the patient should be at 0° . Severe cervical kyphosis can lead to deformity exceeding 90° . Preoperatively, the surgeon should aim for a CBVA of 10° of flexion. The CBVA should not be corrected beyond 0° to allow for appropriate gaze both upward and downward. Overcorrection leaves the patient with an unsteady gait and renders the patient unable to walk downstairs or participate in daily social situations.¹

Plain radiographic findings determine the site of osteotomy and the amount of correction expected. Radiographic evaluation should include full 36-inch length cassette films to evaluate for deformity in the lumbar, thoracic, and cervical spine. These films should be upright. Flexion and extension views should be obtained. The area of the planned

osteotomy can be templated on the X-ray film to estimate amount of correction expected. Both C2–C7 and C7–S1 plumb lines should be measured to assess for the regional and global sagittal imbalance and determine whether it will be corrected with the chosen site of osteotomy. Computed tomography (CT) scan is useful to evaluate bony anatomy, including vertebral body size, areas of previous laminectomy, and osseous landmarks for potential instrumentation. Magnetic resonance imaging (MRI) scan supplements the CT scan and plain radiography. MRI may reveal areas of spinal cord compression that may need to be addressed at the time of surgery. Aberrations in VA anatomy are also revealed on MRI or CT angiogram. It may also reveal areas of potential spinal cord tethering that could complicate the closing of the osteotomy site.

OSTEOTOMY OPTIONS

Posterior Extension Osteotomy

Osteotomy of the cervical spine was pioneered shortly after Smith-Petersen and others described lumbar osteotomy.² Urist reported a single case of a patient with AS with severe kyphotic deformity and a chin-on-chest deformity.³ The patient's flexion deformity necessitated that the procedure be performed under local anesthesia in the seated position with the patient awake. Neurologic monitoring was facilitated by the patient's awake status. The posterior osteotomy was performed at the CTJ. The procedure began with a partial laminectomy at C6 and T1, complete laminectomy at C7, followed by wide resection of the C7 lateral masses. The majority of the C7 pedicles were also taken down. The patient was briefly anesthetized, and the posterior osteotomy was closed with osteoclasis of the anterior vertebral body with gentle extension of the neck. No bone graft was used. The patient was placed in a spinal brace that supported the chin and neck and allowed for gradual manual correction. After final correction over the course of some weeks, the patient was placed in a plaster Minerva for 12 weeks and then encouraged to wear a cervical collar indefinitely when in public. Final correction angle was 64° and the patient's horizontal gaze was restored. He reported only transient, relatively minor, neurologic complications.

Simmons modified the posterior extension osteotomy described by Urist, continuing to use the seated position and local anesthesia rather than prone positioning with general anesthesia.⁴ A halo vest with adjustable rods was used for 4 months followed by soft collar for 2 months. Local bone graft was used to facilitate fusion without the use of internal hardware. Postoperative CT scans were used to assess bony fusion. They reported CBVA correction from an average of 81° to 4° postcorrection in one early group. The second group had average CBVA correction from 49° to 12°. They experienced over 95% fusion rate at the osteotomy site.

Using the posterior extension osteotomy carries with it advantages and disadvantages. Monitoring neurologic status on an awake patient allows for the most accurate observation of any neurologic injuries during surgery, eliminating the false negatives and false positives of somatosensory-evoked potentials (SSEP) and transcranial motor-evoked potentials (MEP) monitoring. Advocates of avoiding internal fixation argue that the use of the halo postreduction allows for correction of deformity outside the operating room, if necessary. In the event of postoperative neurologic compromise, traction via the halo may be

applied to reduce pressure on the offending nerve root. Avoiding internal fixation also significantly shortens operative time and reduces blood loss. When fusing one single vertebral level, the surgeon can avoid long fusion masses and lever arms. This is especially important when considering the poor bone quality in patients with AS when attempting instrumentation. Instrumentation will also be more difficult given the loss of bony landmarks due to either AS or previous trauma or surgery. High rates of fusion have been reported with halo fixation as shown by Simmons, who reported fusion rates >95%. With modern halo vest application, rates of postoperative displacement occur only rarely.

Disadvantages to the posterior extension osteotomy originate from the lack of internal fixation, method of osteotomy, and patient positioning. Halo vest fixation requires a minimum of 4 months of immobilization postoperatively to allow for stable fusion mass. Internal fixation may obviate the need for the halo, though some surgeons support the use of the halo even in the presence of internal fixation due to the poor bone quality, usually found in this patient population. Osteotomy of the posterior elements requires osteoclasis of the anterior column during extension at the osteotomy site. In AS, osteoclasis requires little force during osteotomy closure. In the non-AS, closure of the osteotomy site may require excessive force, leading to uncontrolled osteoclasis and the risk of neurologic injury. In addition, osteoclasis of the anterior elements frequently leaves an anterior void at the fracture site. This can lead to instability, potentially leading to subluxation and potential neurologic compromise in the postoperative period. There is also a theoretical risk of air embolism when performing upright surgery due to negative pressure.

Pedicle Subtraction Osteotomy

Recent reports have described the successful use of a pedicle subtraction osteotomy (PSO) for correction of cervical kyphosis.⁵⁻⁷ The procedure is typically done in the prone position under general anesthesia. With the patient asleep, neurologic monitoring is accomplished via SSEP, MEP, and electromyography. The osteotomy is generally approached at C7-T1, though it may be centered higher if required. A standard posterior approach is used, exposing the spinous processes, lamina, facets, and transverse processes. Instrumentation is performed either before or after resection of the osteotomy, with most authors encouraging fusion of at least three spinal levels above and below the osteotomy level. Where possible, pedicle screws in C7 and

upper thoracic spine and lateral mass screws between C3 and C6 are inserted. Instrumentation may have to include pedicle screws in C2 or even the occiput. If high thoracic kyphosis is present, instrumentation should include the apex of the curve to prevent distal junctional kyphosis. The posterior elements are removed in a similar fashion as in the posterior extension osteotomy. The pedicles are then removed using subsequently larger pedicle taps, followed by decancellation of the vertebral body. The posterior and lateral cortices of the vertebral body are then removed with rongeurs and osteotomes. The surgeon should ensure that the cranial and caudal surfaces of the vertebral body (VB) osteotomy sites are level to avoid creation of a coronal plane deformity. With the near circumferential release of the bone, extension of the osteotomy is possible. As the vertebral body has been removed, closure of the osteotomy site centers anterior to the spinal cord. Rods connect the pedicle and lateral mass screws, and secure the spine in the corrected extended position. Some authors advocate using a temporary flexible rod to unilaterally hold the osteotomy in place to stabilize the cervical spine both before and after reduction. The flexible rod is replaced with the final rod after the contralateral rod is tightened. Bone graft is used to obtain fusion. A halo vest or a hard collar is used for temporary support as the fusion heals.

Deviren et al. reported results for PSO in the cervical spine for kyphosis. Preoperative regional cervical sagittal imbalance was 7.9 cm.⁶ This was corrected to 3.4 cm immediately after surgery, and no loss of reduction was noted on follow-up. The mean PSO correction was 19°, and the mean CBVA correction was 36.7°. There were no reports of pseudarthrosis.

Advocates of the PSO argue that closure of the osteotomy site requires less force and is more controlled with the osteotomy being taken just short of the VB anterior cortex. With the axis of rotation being far anterior at the anterior cortex, the anterior column is not lengthened. Increased cortical contact at the VB osteotomy sites also leads to more stability. Internal fixation may eliminate the need for long-term halo vest application and allows the patient greater mobility. Instrumentation also holds a more rigid construct, lessening the chances of postoperative loss of reduction and possibly improving fusion rates to avoid the need for reoperation. General anesthesia allows for a more controlled surgical theater in the event of adverse outcome given the difficult airway that severe kyphotic deformities can present for anesthesiologists.

Combined Anterior and Posterior Approach

Sasso et al.⁸ describe approaching the osteotomy site both from anterior and posterior exposures. Their technique addresses the anterior gapping, found commonly with the posterior extension osteotomy using osteoclasia to close the osteotomy site. The procedure is performed under general anesthesia, with the first portion being the anterior approach. Some deformities were too severe to allow both anterior and posterior dissections. In these cases, only posterior osteotomies were performed. A standard Smith-Robinson approach was used, and any abnormal ossification was taken down in a controlled fashion. A discectomy was performed at the level of the planned osteotomy. This creates the desired “wedge.” To assist with the posterior approach, the contralateral pedicle (e.g. left pedicle if using a right-sided Smith-Robinson approach) is visualized and resected. If working above the C7-T1 level, the transverse foramen is dissected out to untether the VA during osteotomy closure. When working at C7-T1, this is unnecessary. After the appropriate dissection, the anterior incision is provisionally closed with staples while the posterior portion of the operation is undertaken. The patient is then turned to the prone positioning. The standard posterior approach is then used to expose the desired level of fusion. Pedicle screws in C7 and the upper thoracic spine and lateral mass screws between C3 and C6 are inserted. Before the osteotomy, flexible, hollow stainless steel rods are placed for provisional fixation, preventing subluxation during the osteotomy. After appropriate hardware is placed, the osteotomy is performed. A posterior wedge osteotomy is performed by removing the inferior spinous process, lamina, and inferior portion of the articulating facet of the cephalad vertebral level. At the osteotomy level, the spinous process, lamina, facet joints, and the remaining pedicle are removed. Any remaining transverse foramen is also removed while protecting the VA. The caudal spinous process and portions of the lamina are then removed. One of the surgeons then leaves the surgical field to help control closure of the osteotomy. The remaining, scrubbed surgeon monitors the closure of the posterior elements, dura, and visible nerve roots while SSEP and MEP are monitored. The provisional rods prevent sudden movements during closure and allow for a safer correction. When reduction has been completed, provisional rods are replaced with permanent rods, decortication and bone grafting is completed, and the posterior wound

is closed. The anterior gapping is then addressed as the patient is once again turned supine and tricortical iliac crest bone grafting is placed with an anterior locking plate. After closure, the patient is placed in a Miami-J collar.

Compared to isolated posterior procedures such as the posterior extension osteotomy and the PSO, the so-called “540” procedure offers the advantage of secure fixation both anteriorly and posteriorly. This may offer an advantage in achieving higher rates of fusion and in preventing subluxation of the osteotomy site. It also addresses the anterior gapping seen in isolated posterior extension osteotomies. The anterior release and discectomy may be of benefit when operating on the patient with non-AS where anterior bone is not brittle and may require some force to obtain osteoclasia. Anterior release in these situations may allow for a more controlled closure of the osteotomy site. The most obvious limitation of the “540” is repositioning of the patient with an unstable spine due to osteotomy. However, the authors do not report any complications related to positioning either in final outcomes or with intraoperative neuromonitoring. The anterior approach alone poses challenges in patients with severe kyphosis in gaining the appropriate exposure. Furthermore, the frequently ossified anterior spine in the patient with AS distorts normal anatomy. In these cases, one must frequently rely on posterior anatomy such as the spinous processes to identify the correct operative level.

Flexion Osteotomy of the Cervical Spine

Sengupta et al.⁹ reported a case of a 44-year-old woman with a global kyphotic deformity caused by AS who underwent corrective lumbar osteotomy. Ten years later, she experienced further development of the kyphosis, predominantly at the thoracic level, with resultant restriction of forward gaze. A thoracic corrective osteotomy was performed, which resulted in an upward deviation of her visual field. A flexion osteotomy was then performed at C7-T1. This case report highlights the importance of preoperative planning before performing spine osteotomy. When dealing with patients with fixed kyphotic deformity, one has to consider the effect of the osteotomy on the gaze angle in addition to the global sagittal balance.

POSTOPERATIVE MANAGEMENT

Initial postoperative management varies as determined by the type of osteotomy and fusion chosen. Osteotomies performed without instrumentation require halo vest

immobilization for a recommended 4-month period. Immediate postoperative X-rays and frequent office visits are used to ensure that reduction is maintained. In the event of neurologic deterioration, radiographs should be obtained to ensure alignment is unchanged. Longitudinal traction may be applied through the halo vest to relieve compression of neurologic structures. Before removal of the vest, clinical evaluation is supplemented by radiographic evidence looking for fusion, including a CT scan to assess for union. Once fusion has been established, a rigid cervical collar is continued for 2 months more.

Patients with internal fixation are placed for 3 months in either a rigid collar, such as a Miami-J, or a halo vest depending on the quality of the fixation. Some authors routinely use CT scans to assess for fusion at 1 year. Unlike the use of halo vest immobilization without instrumentation, postoperative adjustments are not possible should neurologic deterioration occur.

OUTCOMES

Urist wrote that his procedure on his patient had a “profound change in her appearance and in her psychological outlook upon life.”³ Indeed, extension of the cervical spine to the near-anatomic position typically results in good to excellent outcomes. Etame et al. reviewed seven studies focusing on the patient with AS and showed that horizontal gaze was restored in all patients. The method of osteotomy varied between studies, as did the method of fixation with internal and external fixation both being employed.¹⁰ All osteotomies were performed at the C7-T1 level. The CBVA was measured preoperatively in these studies, ranging on average, from 41° to 56°. The postoperative CBVA in these same studies ranged, on average, from 4° to 12°. As previously mentioned, care should be taken to avoid overcorrection of the CBVA as this can negatively impact outcomes. Overcorrection may even require reoperation with a flexion osteotomy.

McMaster reported the results of 15 patients with AS treated by an extension osteotomy at the C7/T1 level. The operation was performed under general anesthesia, with the patient in the prone position and wearing a halo jacket.¹¹ Three had internal fixation using a Luque rectangle and wiring. Before operation the mean cervical kyphosis was 23°; this was corrected to a mean of 31° of lordosis, a mean correction of 54°. All the patients were able to see straight ahead. One patient with normal neurological status soon after operation became quadriparetic after 1 week; two others had unilateral palsy of the C8 root, which improved.

There was subluxation at the site of the osteotomy in four patients, and two of them developed a pseudarthrosis that required an anterior fusion.

Samudrala et al.⁷ reported results of eight patients using PSO in a series without patients with AS. All eight patients had correction of horizontal gaze. CBVA preoperatively, on average, measured 36.4° and postoperatively averaged 4°. All patients had internal fixation, with fusion of a minimum of three levels above and three levels below the site of osteotomy. Deviren et al. reported on 11 cases utilizing the PSO technique. The average CBVA correction measured 36.7°, with all patients reporting correction of horizontal gaze.⁶ Simmons et al.⁵ reported the long-term outcomes of a cervical extension osteotomy for AS in 131 patients. They achieved a good correction with the average preoperative and postoperative angles of 56° and 4°, respectively. Two patients had significant neurologic complications, and 18 patients had transient C8 radiculopathy. The incidence of pseudoarthrosis was 4.6%, with 6 patients requiring revision surgery. While no studies compare the outcomes of different types of osteotomies, all studies report correction of the CBVA.

Pain alone is not an indication for a cervical osteotomy. However, a few studies measured pain both preoperatively and postoperatively at final assessment. Belanger et al.¹² reported that 21 of the 24 patients reported improvement in pain. Final assessment showed that 10 of the 24 had no pain, 13 only had mild pain, and 2 complained of moderate pain. No patients complained of severe pain at final follow-up, compared to seven with severe pain before corrective surgery.

■ COMPLICATIONS

Cervical osteotomy, regardless the method of fixation or osteotomy type, carries with it risks of complications. Common complications include halo pin tract infections and wound complications, similar to other posterior cervical procedures. Nonunion is uncommon, but may occur in 5–10% of patients. Treatment requires reoperation with revision fusion. Fewer nonunions have been seen in the limited cases series utilizing PSO and instrumentation, though these reports involve far fewer patients than those reported on by Simmons et al.

Intraoperative bleeding is common, often exceeding 1 L. Instrumented fusions tend to have larger amounts of bleeding. Vascular injury to the VA is possible. Osteotomy below C6 lessens this risk as the VA enters the transverse

foramen most frequently at C6. Carotid artery injury from traction during closure of the osteotomy site has been reported.

Overcorrection or undercorrection of the chin-brow vertical angle tends to contribute to poor outcomes. Undercorrection leads the patient in a similar position as preoperatively. Overcorrection leads to an upward gaze, preventing the patient from performing basic tasks such as walking downstairs, working on a computer, or participating in conversations.

Neurologic injury most frequently involves injury to the nerve root at the osteotomy level, most commonly the C8 nerve root, though this finding is usually transient. Wide decompression of the neuroforamen lessens the risk of radiculopathy. Quadriplegia and paraparesis are rare complications, especially in more recent case series when compared to earlier reports. Careful, wide decompression of the osteotomy site and controlled closure of the osteotomy may lessen the risk of injury to the spinal cord. Osteotomy at the CTJ provides a wider cross-sectional area than higher cervical levels for osteotomy closure. Loss of reduction postoperatively may prove catastrophic and may lead to radiculopathy, paraparesis, quadriplegia, or even death. Pedicle subtraction osteotomy and internal fixation offer theoretical advantages in avoiding this complication by creating a more rigid construct, though loss of fixation has been seen in instrumented osteotomies.

■ AUTHORS' PREFERRED METHOD, AVOIDING PITFALLS, AND COMPLICATIONS

1. *Patient selection:* Clinical and radiological evaluation of the regional and global sagittal imbalance and preoperative optimization of medical comorbidities are essential for good outcomes.
2. *Seated position:* Inpatients with chin-on-chest deformity performing the surgical procedure in the sitting position allows appropriate positioning of the patient and gives the surgeon good control of the head-neck axis (Figs. 49.3A to C). As most of the patients with AS have large fixed deformities, prone positioning is sometime technically challenging.
3. *Correct level of osteotomy:* Intraoperative radiographic confirmation of the correct level of surgery at C7–T1 is important as if the osteotomy is done below T1 in error, the rigid thoracic cage will not allow any correction.



Figs. 49.3A to C: (A) Intraoperative photograph shows the patient in the sitting position with the halo vest and overhead traction on the halo ring to stabilize the head. (B) Intraoperative photograph shows the neck is brought back in a gentle extension arc by the surgeon, not pulled straight backward, to correct the kyphosis by osteoclasia of the anterior column after the osteotomy completion. (C) Intraoperative photograph at the end of the surgical procedure shows correction of the cervical kyphosis and the gaze angle.

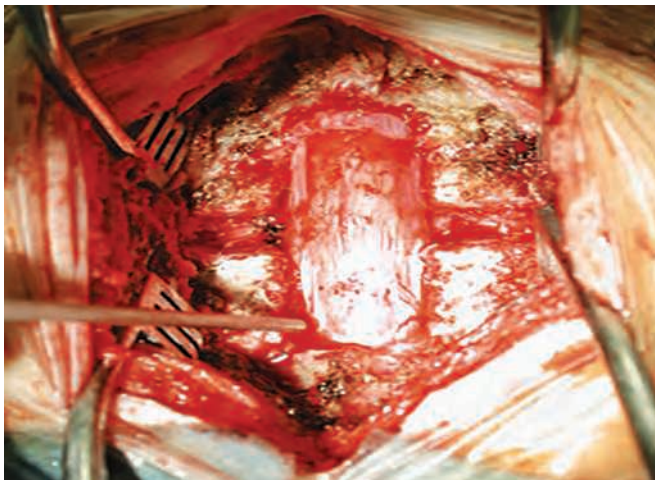


Fig. 49.4: Intraoperative photograph, patient head is at the top, shows wide laminectomy at the level of the osteotomy as well as the caudal and cephalad levels, C7-T1 bilateral lateral mass resection, and foraminotomy.

4. *Adequate decompression:* Wide laminectomy at the level of the osteotomy as well as the caudal and cephalad levels is an important step to allow ample room for the spinal cord after the deformity correction, to avoid spinal cord injury. Bilateral C7-T1 foraminotomy is essential to avoid C8 nerve root palsy after surgery (Fig. 49.4).
5. *Instrumentation:* If used, multiple levels must be included C2-C3 down to T2 to avoid early hardware failure and loss of correction.
6. *Postoperative immobilization:* A halo vest for 3 months, followed by 6 weeks in a cervical rigid collar, may be deemed necessary, even if instrumentation is used to avoid failure of internal fixation and loss of correction, as patients with AS have extremely osteopenic bone and the spine is completely rigid cephalad and caudal to the osteotomy site that creates a significant lever arm.

SUMMARY

Patients with severe fixed kyphotic cervical spine chin-on-chest deformity face major difficulty in their daily activities such as swallowing, performing hygiene, and loss of forward gaze. The goals of the cervical osteotomy are to correct the sagittal imbalance, reverse the kyphotic deformity, and restore the patient's horizontal gaze. Preoperative evaluation is paramount for appropriate patient selection. History should focus on limitations of deformity. Many patients with cervical kyphosis have deformities in the lumbar and thoracic spine, as well as hip contractures that may be contributing to the sagittal imbalance and loss of horizontal gaze. Clinical evaluation to determine the level causing the deformity is essential. Generally, the osteotomy is undertaken at C7-T1 level. Methods of anesthesia, general or local, to operate in a sitting or prone position, type of osteotomy, to use or not use instrumentation—are all debatable and depend solely on the surgeon's preference as each modality has its advantages and disadvantages. No matter what technique is used one should avoid over- or undercorrection. It is recommended to correct to 10° of flexion.

KEY POINTS

- Patients with severe fixed kyphotic cervical spine deformity face major difficulty in their daily activities such as swallowing, performing hygiene, and loss of forward gaze.
- Cervical osteotomy can result in profound change in the patients' appearance, daily functions and in psychological outlook upon life.
- Clinical and radiological evaluation of the regional and global sagittal imbalance and preoperative optimization of medical co-morbidities are essential for good outcomes.
- No matter what technique is used one should avoid over or under correction. It is recommended to correct to 10° of flexion.

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Management of Soft Tissue Injuries of the Cervical Spine: Whiplash Injury and Associated Disorders

David H Kim, Eric Carkner, Gyu Ho Lee

Snapshot

- » Mechanism of Injury and Risk Factors
- » Tissue Injury
- » Natural History
- » Management

INTRODUCTION

Whiplash injury to the neck and cervical spine and whiplash-associated disorders (WAD) continue to represent clinical challenges for evaluation and treatment as well as costly public health problems. One estimate of the minimum annual incidence of WAD in North America and Western Europe is 300 per 100,000 inhabitants.^{1,2} Major obstacles to care include the characteristic absence of diagnostic findings on imaging studies as well as the frequent potentially complicating issues of active litigation or employment/insurance compensation. Over the past two decades, advances have occurred in the understanding of both whiplash injury biomechanics and potential pathoanatomy. Unfortunately, these advances have failed to translate into measurable improvements in patient outcome. Approximately, half of affected patients report continued symptoms for months to years following injury and up to 30% report moderate-to-severe pain and disability.^{3,4} Ongoing controversy surrounds two specific issues: (1) the role of tissue injury in etiology of WAD and (2) the effect of litigation or workers' compensation on natural history and response to treatment.

The term “whiplash” was first used in 1928 by Dr Harold Crowe, an orthopedic specialist, while reporting on eight cases of neck injuries resulting from traffic accidents.⁵ He later expressed regret at his original use of the term that had become widely adopted by the general public and many physicians to imply a specific disease or injury rather than simply a description of motion, which had been his

original intent. The first published medical use of the term “whiplash” came in a 1945 review of cervical spine injuries in the *Journal of the American Medical Association*.⁶ For many years, progress in research and clinical care was hindered by the absence of formally defined terms. The Quebec Task Force on Whiplash-Associated Disorders established the following practical definitions that will be utilized for the purposes of this review: “Whiplash” is defined as “an acceleration-deceleration mechanism of energy transferred to the neck which may result from rear end or side impact, predominantly in motor vehicle collisions, but also from diving accidents, and from other mishaps.” Actual bone or soft tissue injury resulting from such energy transfer is considered “whiplash injury.” The wide variety of clinical symptoms and signs associated with such an event is referred to as “whiplash-associated disorder.”¹

MECHANISM OF INJURY AND RISK FACTORS

Whiplash injury is most frequently observed following rear-end motor vehicle collision.⁷ The term “whiplash” derives from early observations that resulting acceleration of the head exceeds acceleration of the torso that in turn exceeds acceleration of the pelvis—a mechanism which resembles a cracking whip. Early rear-end crash tests demonstrated large neck extension moments resulting from the head rotating backward over low seatbacks. This finding triggered US federal legislation mandating head

restraints in new vehicle construction and has resulted in a significant reduction in the frequency of whiplash injury.

Despite the introduction of head restraints, whiplash injuries continue to occur with relative frequency, indicating the persistence of other potential mechanisms besides simple neck extension over low seatbacks. More recent studies have recognized a complex pattern of spinal segmental motion that has been referred to as “retraction” and which appears to be responsible for generating potentially injurious forces during rear-end collisions. Following impact, forward acceleration of the seatback leads to acceleration of the torso, while inertia of the head resists forward motion. “Retraction” refers to the horizontal translation between upper and lower cervical vertebrae during this stage. As the upper cervical spine accelerates the skull base forward, the head extends until there is contact with the head restraint. Following contact and compression of the seatback and head restraint, the torso and head are propelled forward until the shoulder belt engages to arrest forward torso motion, resulting in forceful head and neck flexion.

Retraction is characterized by rapid transition through three distinct spinal configurations. Prior to impact, the cervical spine is normally lordotic. Shortly after impact, the lower cervical spine is accelerated forward relative to the upper cervical spine resulting in lower cervical spine extension and upper cervical spine flexion. With further forward translation of the lower cervical spine, the upper cervical spine is pulled into extension with head extension occurring as well. Awareness of this more sophisticated injury mechanism has aided in the development of additional safety features such as active head restraint and the Whiplash Protection System.⁸ Such improvements have reportedly been associated with further reductions in rates of whiplash injury.⁹⁻¹¹

Head and neck orientation at the time of impact appears to be a determining factor in the nature and severity of whiplash injury. Head and neck rotation at the time of impact has been associated with increased rates of multiple injuries and development of chronic symptomatology.¹² One magnetic resonance imaging (MRI)-based study has suggested that this position poses potential greater risk of injury to the transverse atlantoaxial and occipitocervical alar ligaments.¹³ It has also been proposed that pre-existing cervical spine malalignment, particularly reversal of normal anatomic lordosis, may also increase the risk of serious injury possibly due to pretensioning of the zygapophysial joint capsular ligaments and interspinous and supraspinous ligaments.^{14,15}

It is unclear if there are other patient-specific risk factors for WAD. Multiple studies have suggested that female gender may be a risk factor for both acute whiplash injury and more chronic WAD, although this association has not been firmly established.^{1,16-22} It has been proposed that this finding may be because that women tend to have more slender necks, and their cervical spines may therefore have less inherent stability and resistance to injury.²³ Studies have reported conflicting findings with respect to the effect of age and general health on risk of injury.

Reflex contraction of neck muscles during rear-end collisions may be a determining factor in whiplash injury. Studies have demonstrated consistent patterns neck muscle activation during rear-end collision, but there appears to be significant variation among individuals. Typically, the sternocleidomastoid muscles are activated early, contracting within 60–90 ms of impact and relaxing within 150–200 ms.²⁴⁻²⁶ The posterior paraspinal muscles are activated within 10 ms of the sternocleidomastoids but typically remain activated following rebound off the head restraint.²⁴ Crash simulations have demonstrated that relatively large forces are transmitted to the head and neck in even low-speed collisions. With a velocity change of only 8 km/h, external forces to the back of the head from the head restraint have been measured up to 500 N.²⁷ Whether reflexive neck muscle contraction mitigates or aggravates injury from these forces or whether variation in muscle behavior affects risk remains unclear.

■ TISSUE INJURY

The absence of readily discernible tissue injury on diagnostic imaging studies remains one of the most frustrating aspects of evaluation and treatment of whiplash injury for both patient and practitioner alike. Despite ongoing neck pain and stiffness as well as an often baffling assortment of associated symptoms such as headache, dizziness, ill-defined visual disturbance, and varying distributions of radiating pain, batteries of diagnostic tests generally fail to reveal any clear abnormality. Increasingly, modern medical practice has become laboratory and test based, so when radiographs and advanced imaging do not demonstrate anticipated pathology such as a fracture or herniated disk, persistent pain and disability are often inappropriately attributed to patient malingering. Nevertheless, significant progress has been made over the past two decades in terms of identifying actual anatomic sources of pain in many if not most sufferers of whiplash injury and WAD.

Zygapophysial (Facet) Joint Injury

Of all the anatomic structures implicated in whiplash injury, the zygapophysial joint has been the target of greatest investigation, and currently, injury to these joints appears to be the most common treatable source of pain in affected patients. Findings from postmortem studies of motor-vehicle accident victims have limited applicability to whiplash injury, given the much different energy levels and vastly different injury mechanisms involved. Nevertheless, autopsies have reported frequent occurrence of nonlethal tissue damage that would be difficult to identify on conventional medical imaging, including varying degrees of both intervertebral disc and zygapophysial joint injury. Observed joint injury patterns range from intra-articular hemorrhage, cartilage fracture, and subchondral bone fracture to more readily diagnosable articular process fracture.^{28,29} These findings suggest at least the possibility that actual gross tissue injury may occur in whiplash injury that is below the threshold of detection of widely available imaging modalities.

Additional support for the occurrence of zygapophysial joint damage during whiplash injury comes from biomechanical studies. In normal healthy volunteers and simulated rear-end collision, cineradiography demonstrated S-shaped deformation of the cervical spine as previously described but also an important upward directed axial load as the torso is accelerated toward the head.³⁰ Following rear-end collision, extension of the lower cervical spine, particularly at the C5–C6 level, is characterized by a nonphysiologic and abnormally high instantaneous axis of rotation. This mechanism may lead to both anterior annular rim avulsion injury as well as direct impaction of the zygapophysial joints with impingement or crush injury of synovial tissue or intra-articular meniscoids as well as cartilage and bone injury.²⁹ Following initial cervical extension and rebound off the head restraint, cervical flexion motion may exceed tolerance limits of the posterior ligaments and joint capsules, and result in a distraction strain injury to these structures. Recently, stretch injuries to the facets have been studied in animal models of whiplash, and the results have supported the theory that this mechanism can generate whiplash-associated pain.^{31–37}

Intervertebral Disc Injury

In the vast majority of patients with whiplash injury or WAD, no clear intervertebral disc injury is apparent. Magnetic resonance imaging evaluation commonly reveals

nonspecific degeneration of disc tissue as well as one or more disc protrusions but nothing that appears to represent an acute injury. One consideration is that MRI evaluation is generally performed later after several weeks or even months and only when expected recovery has not occurred. It is well known that most acute disc herniations spontaneously resolve and the appearance of acute disc disruption may also rapidly improve. In some cases, delayed imaging may not have been performed early enough to demonstrate such injuries. Another complicating issue is the prevalence of asymptomatic disc protrusions and herniations in the general population even in the absence of any history of trauma. Therefore, it cannot be simply assumed that whiplash injury-associated pain and symptoms are due to a disc abnormality visualized on MRI.

Even in the absence of clearly identifiable gross tissue disruption or herniation on MRI studies, subtle but painful disc injury may still be a factor in many patients suffering from whiplash injury and WAD. Biomechanical studies of low-speed collision have demonstrated extension moments and associated strain that on average appears to affect maximally the level of the C4–5 disk.^{38,39} With increasing impact energy, progressively greater strain is observed extending to neighboring disks.

Muscle Injury

Following whiplash injury, patients are often evaluated in the emergency department or by their primary care physician and diagnosed with “cervical strain injury.” In addition to diffuse neck pain and stiffness, neck muscle palpation often elicits tenderness that is interpreted as representing benign and nonspecific muscle tissue injury. Again, MRI evaluation is generally unrevealing and does not demonstrate any gross muscle tear or hematoma formation.

One series of studies, however, has suggested that fatty infiltration of both cervical spinal flexor and extensor musculature may be observed on MRI during the subacute phase in many patients and that this finding appears to be associated with more painful and disabling whiplash injury and may also be a marker for patients at risk for transition to chronic WAD.^{40,41} The same investigators reported consistently greater cross-sectional area measurements of the multifidus muscle in WAD patients and suggested that this phenomenon may represent pseudohypertrophy of the muscle due to higher fat content.⁴² Fatty infiltrates appear to evolve between 4 weeks and 3 months following injury but were not observed in patients with mild or

resolved symptoms. Both disuse and traumatic denervation have been proposed as explanations for these findings, but so far clinical evidence strongly supporting either mechanism remains lacking.

Although neck pain and stiffness are the most common presenting symptoms, dizziness, unsteadiness, and blurred vision are the next most frequent symptoms and may be reported in as many as 70% of patients with WAD.⁴³ The symptom of dizziness, in particular, may represent a risk factor for the development of WAD.⁴⁴ Despite widespread prevalence, no specific pathoanatomic correlates have been identified. In some patients, there may be damage to the peripheral vestibular system, as benign paroxysmal positional vertigo has been observed in as much as half of WAD patients with these symptoms.^{45,46} In a small percentage of patients, prefrontal cortex, brainstem, or vertebral artery injuries have been suspected but never proven.^{47,48}

NATURAL HISTORY

Transition from Acute Whiplash Injury to Chronic Whiplash-Associated Disorder

Motor vehicle collision patients (10–40%) who suffer neck pain go on to develop chronic WAD.^{49–51} A systematic review and meta-analysis has suggested that substantial recovery occurs in most patients during the first 3 months following injury, and this initial period is characterized by a relatively rapid reduction in pain and disability.⁵² Although the pattern of recovery varied widely among patients, a trend was observed toward relatively little further improvement after 3 months. Across multiple clinical studies, the single strongest predictor of developing chronic WAD appears to be initial patient-reported pain level and disability.^{53,54}

Psychosocial Factors

It is generally accepted that psychosocial factors such as depression, coping skills, pain beliefs, and expectation for recovery play an important role in the variable expression of chronic pain in individual patients, especially in terms of how pain becomes disability. In some cases, such factors may amplify otherwise mild and tolerable pain into completely disabling pathology. It is also possible that these factors may prolong pain and disability from otherwise self-limited and recoverable injury.

Data from a population-based cohort study suggests that a patient's own expectation of recovery is a significant

independent predictor of clinical recovery from whiplash injury.⁵⁵ Based on these findings, a large prospective randomized controlled trial of 3,851 whiplash patients was performed in the United Kingdom to determine whether either specialized training of emergency department staff to provide active management consultation to whiplash patients or a course of physical therapy may yield superior outcomes compared to usual care.⁵⁶ The more active consultation was designed to enhance patient expectation of recovery by providing direct individualized education about the benign nature of their injury and the likelihood of rapid improvement through simple resumption of routine physical activity. Unfortunately, at 12 months follow-up, no significant difference in neck disability index score was observed between groups. More active counseling by emergency department staff yielded no discernible benefit, and although the physical therapy provided a modest benefit in terms of accelerated recovery, the difference was not found to be cost-effective and was not recommended.

It has been proposed that the transition from acute whiplash injury to chronic WAD may be mediated in part by maladaptive changes in central pain processing. According to this theory, a traumatic experience with or without accompanying tissue injury can trigger a hyperexcitable state within the central nervous system and lead to lasting impairment of endogenous pain mitigation. Neurophysiologic changes in the central nervous system have been observed in both the brain and spinal cord in association with chronic low back pain, fibromyalgia, and whiplash injury.^{57–59} This altered state can lead to affected patients experiencing pain with normally nonpainful stimuli, greater than expected pain with mildly painful stimuli, and significantly expanded pain distributions.⁶⁰

A popular biopsychosocial model for the development of chronic musculoskeletal pain is the fear-avoidance model. This theoretical model postulates that a subpopulation of patients with initial benign musculoskeletal pain following injury suffer excessive fear and anxiety that such pain signifies ongoing tissue injury and therefore go to great lengths to avoid physical activity and movements that may provoke pain. The result is a downward spiral of disuse-related weakness and deconditioning, persistent or worsening pain, disability, fear, and anxiety.⁶¹

The two central concepts of fear-avoidance behavior are catastrophizing and kinesiophobia. Catastrophizing refers to exaggerated negative interpretation of actual or anticipated pain.⁶² Although research has suggested that

level of catastrophizing is associated with current levels of disability in neck pain patients, the data with respect to prognostication is mixed.^{63,64} Kinesiophobia refers to pain-related fear of movement or activity. Again, the data with respect to prognostic value of observed kinesiophobia in terms of transition from acute whiplash to WAD is indeterminate.^{3,65} At this time, although the fear-avoidance model is widely believed to be a significant factor in the development of chronic low back pain and disability associated with both injury-associated and nontraumatic scenarios, there remains little clinical evidence that this is a determining factor in a majority of patients suffering from WAD.

Finally, 15–25% of WAD patients may suffer from some element of post-traumatic stress disorder (PTSD).⁶⁶ In patients who describe symptoms of repeatedly re-experiencing, the traumatic event cognitive behavioral therapy may be effective in reduction of the PTSD symptoms specifically.⁶⁷

Genetic Factors

It is widely recognized that the same type and severity of tissue injury in different individuals are associated with wide variation in reported pain levels. The propensity to develop chronic pain and symptomatology following injury is similarly variable. At least some of these population-wide variations appear to be due to genetic factors. Prevalent polymorphic variations of the catecholamine-O-methyltransferase gene (*COMT*) and guanosine triphosphate cyclohydrolase genes (*GCHI*) have been shown to affect persistent pain levels following spinal fusion surgery.^{68,69} A genetic study of patients presenting to the emergency department immediately following a motor vehicle accident revealed that patients with specific pain-sensitive forms of *COMT* were twice as likely to report moderate-to-severe neck pain and dizziness and three times as likely to report moderate-to-severe headache.⁷⁰ Of interest, compared to patients without the pain-sensitive forms of the gene, these patients also estimated that physical recovery would require on average twice as long.

Predictors of Outcome

The most recent natural history data suggest that by 1 year after whiplash injury as many as 50% of patients continue to be symptomatic.⁷¹ The Quebec Task Force on Whiplash-Associated Disorders generated a grading system that has performed poorly in terms of predicting chronic pain

and disability in individual patients. In the vast majority of published cohort studies, initial level of reported neck pain remains the single most predictive factor in terms of recovery with higher levels of pain portending poorer long-term prognosis.^{52–54} One prospective study suggested three different patterns of recovery over the first year.⁷² About 45% of patients reported initial mild levels of pain and disability, and demonstrated rapid and complete recovery. About 39% of patients reported initial moderate levels of pain and disability and demonstrated slower recovery to the point of persistent mild symptomatology at 1 year. About 16% of patients reported initial severe levels of pain and disability and continued to report chronic moderate-to-severe symptoms at 1-year follow-up. Another review combined results from eight different studies and identified a cutoff point for visual analog scale pain score of 5.5 out of 10 beyond which patients demonstrated over five times the risk of developing chronic pain or disability.⁷³

Although initial pain level is the strongest predictor of developing chronicity, variation in initial pain level accounted for only 15.7% of the variation in pain and disability observed at 1 year in one study.⁷⁴

Several studies have suggested that presence of associated symptoms such as headache, dizziness, upper extremity pain, numbness, or paresthesia may also be risk factors for chronicity, although correlations with these symptoms have been inconsistent.⁵³ Symptoms of insomnia and reported cognitive impairment have not been consistently associated with prognosis.

Among crash-related factors, not wearing a seatbelt appears associated with increased risk of chronic pain and disability.^{73,75} Among sociodemographic factors, female gender and lower levels of formal education have been frequently reported risk factors, while age appears to have little predictive value.⁷⁵ Pre-existing neck pain represents a small but significant risk factor.⁷³ In terms of physical findings, diminished neck range of motion may be a risk factor for chronicity with one study showing a nearly five-fold increased risk of disability at 1 year when decreased neck motion was measured on initial evaluation.^{3, 54,76} In multiple studies, patients who demonstrated lower levels of measured cold pain tolerance tended to experience poorer recovery.^{3,77} Findings with respect to various psychosocial factors have varied considerably across studies with generally weak evidence, suggesting that depression, poor coping skills, fear-avoidance behavior, and pain

catastrophizing may be associated with poorer outcome.⁷⁸ By contrast, patients who reported lower expectations for recovery were found to suffer higher degrees of chronic pain and disability, suggesting the possibility that a patient's own expectations may be an important prognostic variable.⁵⁵

Cultural factors may be a determinant of long-term disability perhaps due in part to influence on patient expectations. A so-called "whiplash culture" has been described in specific countries such as the United States, Canada, and the United Kingdom.⁷⁹ Overall rates of chronicity appear dramatically higher in these countries compared to inhabitants of Germany, Greece, and Lithuania.^{79,80} The Netherlands may also represent an environment that promotes chronicity following whiplash injury, with one report revealing 21.7% of patients continuing to be work disabled 1 year following injury.⁸¹

Although the issue remains controversial, some studies have suggested that legal representation as well as compensation through a tort-based insurance system may prolong recovery.^{18,82} The so-called "compensation hypothesis" proposes that compensation factors are directly or indirectly associated with worse outcomes following injury and that this relationship may account for more chronic and severe pain and disability that is observed even in the absence of observable tissue injury. This phenomenon has been attributed to insurance and medico-legal systems in which patients are expected to prove the extent of their poor health and functional disability in an adversarial setting and in which the amount of their compensation is directly tied to the severity of their condition. The hypothesis has been supported by studies reporting poorer outcomes associated with lawyer involvement and tort-based compensation systems.^{16,18,83-86} However, multiple investigators have vigorously challenged the validity of such conclusions on the basis of methodologic bias in the referenced studies, including the problem of reverse causality because that more severely injured patients are more likely to pursue compensation. As a result, it is reasonable to assume that the status of compensation is also the direct consequence of more severe injury.⁸⁷

MANAGEMENT

The initial evaluation of a patient presenting with neck pain following a whiplash-type injury mechanism should follow guidelines established and previously presented in this textbook regarding evaluation and management of cervical spine trauma. Initial history and physical examina-

tion should be directed toward determining the likelihood that a more serious and potentially unstable cervical spine injury has occurred. Appropriate plain radiographs and/or computed tomography (CT) should be obtained to rule out conditions such as spinal fracture or dislocation. It is critical for the lateral X-ray to include the cervicothoracic junction to avoid missing injuries in the lower cervical spine. In the setting of high set shoulders or incomplete imaging, it is imperative to obtain a CT scan. In the setting of neurological symptoms or deficits on examination, advanced imaging such as MRI or CT myelogram is required to rule out spinal cord or nerve root compression that may indicate the need for early surgical decompression. Ligament disruption resulting in potentially dangerous spinal instability may be apparent during initial evaluation, but acute muscle spasm may delay recognition of this type of injury until subsequent follow-up evaluation days to weeks later. Therefore, patients unable to provide adequate flexion-extension views on plain radiographs should be placed in a hard collar until their cervical spine can be clinically cleared. If a ligamentous injury is suspected, an MRI can be used to evaluate discoligamentous injuries.

When patients have been cleared of osteoligamentous injury, ongoing neck pain and stiffness are often provisionally diagnosed as cervical strain or acute whiplash injury. In the absence of a neurological deficit on examination, arm pain symptoms alone do not mandate initial evaluation with MRI. Appropriate evaluation of the upper extremity itself, however, may be required depending on the presence of additional findings on history or examination. Persistent pain on follow-up evaluations should prompt consideration of advanced imaging such as MRI, particularly if pain levels are not significantly improved by 6 weeks postinjury. The absence of more specific diagnostic findings such as cervical disc herniation, stenosis, or ligament injury supports an ongoing working diagnosis of cervical strain or acute whiplash injury.

Objective findings on physical examination are limited. Patients are generally found to be neurologically intact and any positive findings are typically nonspecific. The most common manifestations of whiplash injury and WAD are abnormal neck posture and motion, including restricted global patient-generated active range of motion and disordered patterns of movement.^{48,88} Specific characteristics include reduced acceleration and velocity of active neck movement, reduced smoothness, and irregular axes of movement.⁸⁹⁻⁹¹ These findings are most likely due to pain-related inhibition of normal movement as opposed to any readily identifiable structural disturbance.

Currently available clinical practice guidelines for the management of whiplash injury and WAD remain relatively vague. Typical recommendations focus on patient reassurance regarding the benign nature of whiplash injury and advice for continuing routine physical activity as tolerated.^{92,93} Nonspecific exercise is also commonly advised.⁹⁴

Despite an abundance of more active treatment options, there remain few with good clinical evidence supporting efficacy. Symptomatic use of nonsteroidal anti-inflammatory medication is reasonable as is use of local cold or heat therapy. Although these may provide temporary alleviation of pain, there is no evidence demonstrating that any medications or modalities foreshorten the overall period of pain or disability. If stronger narcotic pain medications or muscle relaxants are prescribed, it is recommended that these be provided for short-term relief of acute symptoms only.

Patient education appears to be an important component of efficient recovery. A prospective randomized trial comparing four weekly information sessions to usual care showed superior results among patients receiving more intensive personal education.⁹⁵ Even viewing an educational video appears to provide a modest degree of improved recovery over standard care.⁹⁶ Simply handing out educational pamphlets appears to provide no measurable benefit above standard care.⁹⁷

Physical therapy may be of benefit when utilized after the acute postinjury phase. A prospective randomized trial of treatment during the acute period compared a 6-week course of physical therapy to a 1-hour information session with a nurse and found no observable advantage from the physical therapy.⁹⁸ However, a randomized trial from Sweden demonstrated that physical therapy performed in more delayed fashion was associated with significant improvement in neck pain and headache at 6 months.⁹⁹ If some form of physical therapy is prescribed during the acute phase, neck mobilization may be the most beneficial prescribed treatment given that more rapid recovery has been observed with mobilization exercises compared to collar treatment and rest.^{100,101} Passive modalities such as diathermy, hydrotherapy, heat, and cold treatments have not been shown to be of clear benefit.^{79,102} Similarly, there is insufficient evidence to recommend other interventions in the acute phase, including pharmacologic agents, injection-based treatment, traction, or spinal manipulation.¹⁰² A Cochrane Review of nonoperative treatment for acute, subacute, and chronic WAD has concluded that there is insufficient evidence to support any specific exercise regimen.¹⁰³

While numerous studies have failed to demonstrate any benefit from medical intervention to treat acute whiplash injury, there is good data suggesting that excessive health care interactions during the acute postinjury phase may actually be detrimental in terms of speeding recovery. In one study, both options of a multidisciplinary outpatient rehabilitation program and directed fitness training within 120 days of injury were associated with slower recovery compared to usual care.¹⁰⁴ This trend was also observed in another Norwegian study of multidisciplinary care.¹⁰⁵

Medial Branch Blocks

Clinical evidence supports specific treatment of pain originating from the zygapophysial joints. Prior to treatment, cervical spine medial branch blocks are required as a diagnostic test for pain originating from these joints.¹⁰⁶ This approach involves anesthetizing median branch nerves that innervate a specific joint with a small volume of local anesthetic. Using this method, it has been estimated that as many as 50% of patients suffering chronic neck pain may have a component of pain originating from one or more joints.¹⁰⁷⁻¹¹⁰ However, it should be noted that this finding has also been observed in chronic neck pain populations regardless of whether a history of whiplash injury is present.¹¹⁰ The most commonly affected segments, based on response to such blocks, appear to be C5–C6, C2–C3, and C6–C7.²⁹ Although there is little evidence for the success of intra-articular facet injections, anecdotally facet injections can also be useful for whiplash-based pain.

Radiofrequency Neurotomy

If patients respond favorably to diagnostic medial branch blocks, radiofrequency neurotomy can be an effective treatment option. A randomized, controlled, double-blind trial enrolling 24 patients with neck pain following motor vehicle accidents demonstrated superior results in treated patients.¹⁰⁹ All patients in the study had presumed zygapophysial joint pain based on response to diagnostic blocks. The control patients received sham treatment in which the radiofrequency current was not turned on. The median time required for pain to return to 50% of pretreatment levels was 263 days in the study group versus 8 days in the control. In terms of complications, several patients reported prolonged numbness in the territory of the injected nerves, but none considered the localized sensory loss troublesome.

This treatment also appears effective for cervicogenic headache thought to arise from the third occipital nerve branch arising from the posterior division of the C3 nerve root of the C2–C3 segment.^{111,112} In terms of headache, neurotomy has been associated with pain relief lasting a median of nearly 300 days.

Following initial successful treatment results, pain typically recurs gradually over a year or so secondary to nerve regrowth. Repeat treatment generally re-establishes good pain relief but often for progressively shorter intervals.¹¹³

CONCLUSION

Current best evidence suggests that actual tissue damage is an important etiologic factor in generating pain and disability in WAD. The absence of observable tissue injury on advanced spinal imaging should not be interpreted as signifying the absence of true injury or WAD. Although the pattern of injury may be variable, lesions affecting the zygapophysial joints currently appear to be the most common identifiable and treatable injury. Once started, maintenance of WAD-related symptoms and disability may often depend at least in part on fear-avoidance behavior and psychobiological factors. There is currently no consensus regarding the role of litigation and/or workers' compensation on WAD natural history or disability. Inconsistent findings by different studies may be due in part to significant differences in litigation environment and workers' compensation systems in different regions and countries.

Regardless of the presence of psychosocial factors such as depression and anxiety disorders, legitimate injury remains the critical triggering and determining factor in most cases. Often, effective pain relief methods lead to parallel reduction of the psychological and behavioral manifestations of these other conditions.¹¹⁴

At this time, a patient-specific personalized approach to treatment is limited by the absence of strong predictive factors indicating patients at high risk of chronicity. From a practical standpoint, it is reasonable to simply provide education and reassurance regarding the generally benign nature of uncomplicated whiplash injury, encourage continuation of work and physical activity, and monitor symptomatology during the acute postinjury time period. Patients who fail to demonstrate expected levels of recovery after 2–3 months should be the target of more extensive evaluation and treatment.

Unfortunately, at this time there is no good clinical evidence that any proposed risk factor is modifiable to the extent of affecting natural history.

There is little data to support a role for surgical treatment other than in cases of clearly defined anatomic derangement such as cervical spine fracture, dislocation, or ligament disruption resulting in instability. Surgery is also appropriate in the setting of ongoing pain or neurological deficit associated with disc herniation or spinal stenosis. However, these conditions represent distinct diagnostic entities that should be excluded upon initial evaluation, and by definition, are not a component of simple whiplash injury. In select cases, surgery may be an option for patients with presumed discogenic pain emanating from one or two levels, although this remains highly controversial.

For patients with potential zygapophysial joint-related pain suggested by response to multiple diagnostic medial branch blocks, radiofrequency nerve ablation treatment is a reasonable option that has been associated with lasting pain relief. Surgical treatment in this population has not been formally evaluated or reported and cannot be recommended at this time.

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Closed Management of Cervical Spine Injuries

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Snapshot

- » Methods of Closed Treatment
- » Cervical Traction and Reduction Methods
- » Injuries of the Upper Cervical Spine
- » Subaxial Cervical Spine Fractures
- » Cervical Burst and Flexion Teardrop Fractures

METHODS OF CLOSED TREATMENT

Orthoses

Orthoses are externally applied devices that restrict motion, correct deformity, or improve function when a pathologic or iatrogenic process has impaired stability.¹ Spinal orthoses can be divided on the basis of the spinal segment they immobilize: cervical orthoses (CO; soft or hard collar), cervicothoracic (CTO; 4 post collar, SOMI or sterno-occipito-mandibular immobilizer, halo-thoracic vest), thoracolumbar (TLO or Jewitt hyperextension brace), thoracolumbosacral (TLSO clamshell, anterior spinal hyperextension brace) and lumbosacral (LSO).²

Noninvasive Orthoses

A soft collar provides comfort but limited immobilization. It is commonly used in whiplash injuries or muscle strains to minimally restrict motion and acts as a patient reminder to avoid excessive motion or strain. Hard collars (Fig. 51.1) are available in several forms including the Aspen collar (Aspen Medical Products, Irvine, CA, USA), the Miami J (Ossur Americas, Foothills Ranch, CA, USA), and the Philadelphia collar (Philadelphia Cervical Collar Co., Thorofare, NJ, USA). The common design in these orthoses is a firm seating superiorly between the occiput posteriorly and the mandible anteriorly, and the upper thorax



Fig. 51.1: Cervical hard collar.

inferiorly. Most collars also include an anterior opening for a tracheostomy. Hard collars are used to immobilize the middle cervical spine and are generally reasonably effective in immobilization of the spine in flexion and extension, more so than in lateral flexion and rotation.³ Although a number of choices are available, in vivo evidence suggests that most of these orthoses are equivalent in efficacy.⁴ Patient choice and comfort, as well as prescriber experience should be considered in choosing an appropriate device. Cervicothoracic orthoses, like the SOMI brace and

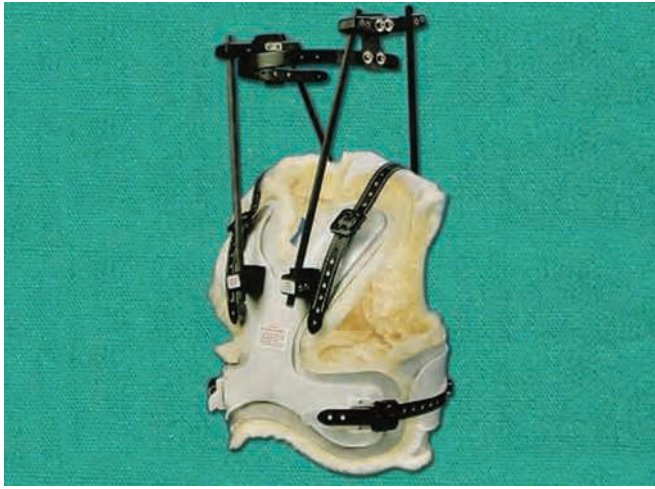


Fig. 51.2: Halothoracic vest.

the Minerva brace (United States Manufacturing Company, CA, USA) are particularly useful for immobilizing the lower cervical and upper thoracic spine. Typical cervical hard collars lack effectiveness across this level.⁴

Complications from the use of noninvasive collars are relatively rare but do occur when they are used inappropriately.^{2,5} Consultation with an experienced orthotist is essential in limiting these sometimes significant events. Skin breakdown over the suprascapular areas and bony prominences, such as the occiput, mandible and sternum, occur especially in polytrauma patients and those with altered consciousness or loss of sensation. Rash, muscle atrophy and psychological dependence have been reported with orthoses.⁵ Hard collars have been shown to cause a small but significant increase in intracranial pressure.⁶ This may be especially important in severe head injury patients and hard collars should be removed at the earliest opportunity once the cervical spine has been cleared of injury.

Halothoracic Vest

The halo vest is a CTO that allows the most rigid immobilization of the cervical spine amongst all braces (Fig. 51.2). It is most effective in the upper cervical spine and across the occipitocervical junction.⁷ Although it is invasive and cumbersome, it remains an effective and accepted method for managing a number of cervical injuries and postsurgical instability. Patient discomfort, social stigma, cosmetic concerns and pin site scar formation are universal issues with a halo-vest and need to be addressed carefully by the treating surgeon to ensure good compliance. In a recent

survivorship analysis, 74% patients completed the prescribed period of halo vest without early removal, and in 85% of cases, treatment with halo vest was successful without revision to surgical management.⁸

The halo consists of a ring, four upright connecting rods, and a vest. In current practice, the ring is made of light weight radiolucent composite graphite materials. The “ring” is actually 2/3rd of a ring which opens posteriorly to allow a patient to lie supine. It is attached to the skull typically with 4 stainless steel pins. The vest is also lightweight and made of thermoplastic material. A noninvasive halo (NIH) consisting of a halo mask has been proposed as an alternative to invasive halo based on skull pins. Although an attractive option, there is insufficient data to establish its equivalence to the traditional halo-vest.⁹ The halo ring can also be used as a traction device instead of Gardner-Well tongs. This technique has the advantage that the traction device can be easily converted to a halo vest for definitive management. Contraindications for the halo include cranial fractures, infection, severe soft tissue injury at the proposed pin sites, cachexia, severe deformity, morbid obesity, poor compliance and patients with mental health disturbance.³

Application of the halo ring and vest follows a series of steps.¹⁰ It is often applied in a supine patient in spinal immobilization precautions. The use of several assistants for positioning and turns is mandatory. The first step is to determine the appropriate ring size (about 2 cm distance between the skin and the ring) and vest size. Pin sites are then shaved and prepared with antiseptic solution. The ring is then temporarily held in place by 3 positioning pins with plastic caps. The skin and deep tissues over the pin sites, including the periosteum, are infiltrated with local anesthetic. In adults, two anterior pins and two posterior pins are positioned within the ring. The anterior pins are placed 1 cm superior to the orbital rim, over the lateral two thirds of the orbit, below the level of the largest circumference (equator) of the skull, and should be placed with the patient's eyes closed to avoid skin tension. Placement of the posterior pins is more variable. They are usually placed 1 cm above the helix of the ear, below the level of the equator. The ring should be clear of any contact with the ear. Pins should be placed as perpendicular to the skull as possible to avoid complications.¹¹ The pins are tightened diagonally in 2-inch-pound increments up to 8 in-lb torque.¹⁰ Finally, locking nuts are then applied to prevent the pins from backing out. The vest is then applied and fixed to the

ring according to the steps outlined by each manufacturer. Careful adjustment can be performed using the vest apparatus to apply angular, compression, or distraction forces to the cervical or cervicothoracic spine. All pins should be retightened at 24 to 48 hours after initial insertion. In children, it is recommended to use multiple pins at low insertion torque (2–5 in-lb) because of their thin and pliable skull.^{12,13} Custom made rings and vests are often required.

Minor complications are frequent with prolonged use of the halo vest. Pin loosening is reported to occur in up to 60% patients.¹⁴ In the absence of signs of either superficial or deep infection, pins should be carefully retightened to 8 in-lb. If no resistance is met during insertion, a new pin at another location should be placed. Pin site infections occur in up to 13%.⁸ Initial treatment is local wound care and oral antibiotics. If conservative treatment fails to resolve the problem, the pin should be removed and replaced at a new site.¹⁰ Pressure sores from the vest and straps have been reported in up to 10% of patients.¹⁵ The physical limitations of the orthotic include swallowing difficulty and deglutition dysfunction, which can result in aspiration, especially in the elderly.¹⁶ Restriction of pulmonary function, pneumonia and thromboembolism have also been reported.^{14,17}

Other local complications include injuries to the supraorbital nerve, supratrochlear nerve, greater occipital nerve and zygomaticotemporal nerve from incorrect pin placement. Frontal sinus violation and skull fractures may occur from incorrect placement. Anterior pins that are placed too far laterally may cause inner table and dural penetration. The pin needs to be replaced and the dural tear usually heals with 4–5 days of conservative care including elevation of the head of the patient's bed.¹⁴ Although extremely rare, epidural abscess or meningitis may occur from inner table violation.

Halo vest use in elderly has significant morbidity and mortality^{18–20} in most studies, although evidence suggests that the reported high incidence of respiratory complications may have been overestimated.¹⁷ In either case, the use of invasive immobilization may impair mobility and be met with minor complications that have a more profound effect on those patients with a marginal medical status. As discussed later in this chapter, the use of an invasive orthotic in this group of patients should be measured against the lower risk of other devices, even if they are somewhat less effective at controlling motion or stability.

'Snaking' or paradoxical motion has been defined as movement in opposing directions at adjacent levels,

especially where the extremes of the spinal region are rigidly fixed.²¹ It has been shown to occur with all braces, including in the halo-vest. The significance of this issue lies in diminishing the immobilizing capacity of cervical braces and the halo vest especially from occiput to C2, and in the middle of the subaxial spine.²¹ Inadequately fitting braces and vests have been shown to increase 'snaking'.^{21,22}

CERVICAL TRACTION AND REDUCTION METHODS

Traction

Skeletal traction has been used for decades to reduce and sometimes definitively treat injuries of the cervical spine. A number of different methods are available, generally using an invasive device to attach to the skull combined with a system of weights. Countertraction is generally accomplished with body weight alone, but countertraction devices have also been employed.²³ Traction techniques may be used to treat malalignment and dislocations at any level of the cervical spine, although the specific methods involved and the chances of success vary in the lower cervical spine compared to the upper region.²⁴ Traction is most commonly described for flexion-distraction injuries (facet subluxations or dislocations), as well as cervical burst fractures, odontoid fractures, and spondylolisthesis of the axis.^{24–31} Contraindications to using traction include any distraction type injury (such as occipitocervical dislocation or Type IIA spondylolisthesis of the axis), as well as skull trauma that precludes the use of an invasive clamp.^{31–33}

Cervical traction requires a cooperative patient who may be examined before, during and after any manipulation. In practical terms, the setting is also critical. In many hospitals, the close monitoring of patients requires advanced physician and nursing care which is typically available on high observation wards or emergency rooms. All equipment should be prepared and immediately available, including radiology equipment for radiographic follow-up. It is also critical to plan for an unexpected neurologic deterioration. As described later in this chapter, a number of case reports have described sudden and catastrophic neurologic injury during cervical dislocation reduction.³⁴ If any neurologic deterioration should occur, traction should be stabilized or removed, radiographs should be obtained immediately, and other prompt investigations should be pursued to determine if a new compressive pathology has been created.



Figs. 51.3A and B: Gardner-Wells traction. (A) Positioning and application of tongs in posterior location to reduce a facet dislocation. (B) Inline traction using a rope and pulley system.

Various devices may be used to capture and control the skull. The most popular choices include a halo ring and Gardner-Wells tongs.^{35,36} Tongs may be applied quickly, even by those inexperienced with the technique, although the overall pull-out strength of the device is lower than a halo ring.³⁶ With the patient appropriately positioned, the scalp is prepared with antiseptic solution and local anesthetic is infiltrated in to the skin. For Gardner-Wells tongs, pins are usually inserted 2–3 centimeters above the pinna of the ear, and 1–2 centimeters posterior to the external auditory canal (Fig. 51.3A). This position avoids damage to other structures such as the superior temporal artery. The pins are symmetrically advanced until a piston within the pins pushes outwards to become flush with the pin head. The posterior position allows for slight flexion of the neck, which assists in the reduction of dislocations and other flexion or compression injuries.²⁸

Sequential weights are then applied to the ring via a rope and pulley system (Fig. 51.3B). It is critical to provide adequate analgesia for the patient to maintain their comfort and cooperation. Narcotic analgesics, muscle relaxation, and mild sedatives are all useful adjuncts. The time required and amount of weight varies in different published descriptions of the technique.^{24,28,29,37} Typically, between 5 and 10 kg is used to begin, which roughly offsets the weight of the head. A small period of time is allowed to ensure that the patient is comfortable and to permit any stretch or creep. Different authors describe waiting from 2 to 30 minutes per step, although the decision regarding rapidity of the reduction should be assessed depending on the clinical situation and patient factors.^{24,28,37} Weight

is then added in 5 kg increments.²⁴ The total amount of weight allowable can vary up to approximately 55 kg or 80% of the patient's body weight.^{28,29} Higher amounts of weight are generally required for fractures lower in the cervical spine, as well as for bilateral and nonfractured injuries (i.e. pure facet dislocation). For each level away from the skull, an additional 5–10 kg may be required beyond the initial 10 kg.^{28,38} It is critical to perform both clinical and radiographic assessments frequently during reduction. Mobile X-ray equipment is a helpful adjunct if traction is applied on a routine hospital ward. In some cases, gentle manipulation or adjustments may be required. Flexion of the neck by altering the trajectory of the weight and counterweight often assists in reducing flexion distraction injuries such as facet dislocations.³⁸ In the case of a unilateral injury, lateral rotation towards the injured side may force the dislocated inferior articular process to clear the superior facet below and reduce into anatomic alignment. These manipulation maneuvers must be done carefully in a relaxed patient to avoid complex motions that may increase the risk of neurologic injury such as nerve root palsy or cord injury.³⁷ If reduction is obtained and confirmed radiographically, traction and flexion are reduced or removed and a decision is then made with regards to definitive treatment. In the case of halo ring traction, a vest may be applied as either temporary stabilization until an operative procedure, or may be used as definitive treatment in some cases.^{39–41}

Several complications may occur from cervical traction in addition to those caused by the skull clamp itself. These include 6th cranial nerve palsy, osteomyelitis,

pressure sores, scalp hemorrhage, and failure of the clamp.^{42,43} These are generally avoided with proper technique and good nursing care.

INJURIES OF THE UPPER CERVICAL SPINE

Occipitocervical Dislocation

Occipitocervical dislocations are high energy injuries and are usually fatal, but more survivors are being reported because of improvement in on-scene emergency management as well as diagnosis and definitive management.³² These injuries are also found more commonly in pediatric cervical spine trauma than previously thought.³²

Traction is contraindicated in these injuries and the initial management is with halo-vest immobilization.³² Radiographic parameters to diagnose this injury include the Power's ratio and the Harris lines (basion-dens interval and basion axial interval). Criteria for diagnosis include.^{44,45}

- Power's ratio > 1,
- Basion-dens interval > 12 mm,
- Basion axial interval > 12 mm or < 2 mm
- Widening of the O-C1 joint.

In equivocal cases, an MRI may provide valuable information regarding the integrity of the anterior and posterior atlantooccipital membrane, tectorial membrane, apical, alar and cruciate ligaments (the craniocervical stabilizers) in these difficult injuries. These injuries are considered highly unstable and surgical occipitocervical fixation is recommended. With advanced imaging modalities, however, a new subgroup of patients with normal parameters on X-ray and CT but signal change on MRI in the posterior ligaments or occipitoatlantal joints have emerged.^{46,47} This subgroup can be managed with collar or halo-vest, unless there is unequivocal evidence of complete disruption of the craniocervical stabilizers on MRI. Due to potential for catastrophic neurological injury, extremely close follow-up with radiographs is mandatory.

Occipital Condyle Fractures

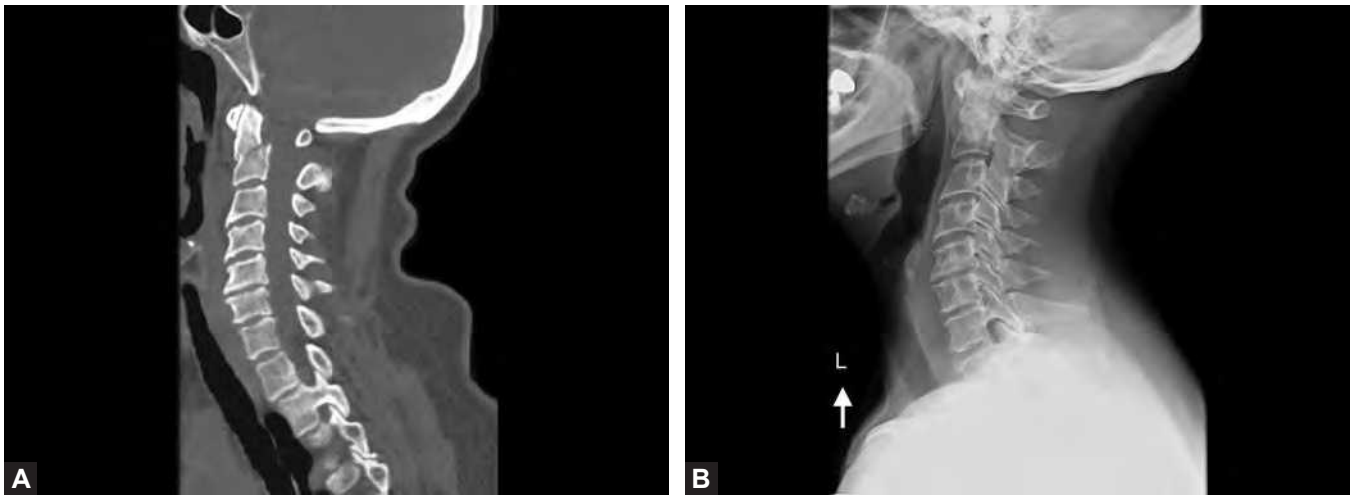
Occipital condyle fractures are becoming recognized more frequently in recent years as a result of advances in imaging and patient survival.⁴⁸ These fractures may be a part of disruption of the atlanto-occipital complex.⁴⁸ They are most frequently the result of high velocity injuries, especially motor vehicle collisions. Anderson and Montesano

classified these fractures into 3 types.⁴⁹ Type 1 injuries are comminuted, impaction fractures, Type 2 fractures extend into the skull base and Type 3 injuries are alar ligament avulsion fractures. Type 3 is the most common and Type 1 is the rarest. Traditionally, Type 1 and 2 fractures were considered stable and treated nonoperatively, whereas Type 3 fractures were considered unstable and occipitocervical fusion was recommended.

Recently, this guidelines has been refuted. It has been proposed that it is the only the presence of associated occipitocervical instability that dictates the need for surgical fixation.^{50,51} Subsequently, it has been confirmed that even Type 3 injuries and bilateral fractures can be managed nonoperatively if there is no evidence of occipitocervical instability or associated cervical fractures.^{48,52} Use of a hard cervical collar for 6 weeks is usually adequate and a halo-vest is usually not necessary for management of these injuries.^{48,52}

C1 Fractures

The most common C1 fracture requiring treatment is a vertical compression or burst fracture (Jefferson fracture). The stability of these injuries is judged based upon the integrity of the transverse ligament.^{53,54} If the sum of the C1 lateral masses overhang (measured on an open mouth view or a coronal CT) with respect to the C2 lateral mass is greater than 7 mm, the transverse ligament is considered disrupted (rule of Spence).⁵⁵ Alternatively, MRI is highly sensitive for diagnosing transverse ligament disruption. Regardless of the diagnostic method, complete disruption of the transverse ligament is a contraindication for closed treatment. Fractures with no evidence of transverse ligament disruption as well as avulsion fractures of the transverse ligament are amenable to healing with external immobilization, in a hard collar or halo-vest for 8–12 weeks.⁵³ Closed management can also be used to minimize surgical treatment even when transverse ligament disruption is present. Initial management of an unstable C1 fracture in a halo-vest typically results in healing of the bony injuries, resulting in isolated atlantoaxial instability. Subsequent surgery involves only C1–C2 arthrodesis, thus occipitocervical fusion can be avoided. Finally, atlas fractures are frequently associated with odontoid or other C2 fractures. These fractures generally involve only the posterior arch. In these circumstances, the associated injuries dictate the management unless the atlas fracture by itself is unstable.^{53,54}



Figs. 51.4A and B: Type II odontoid fracture with minimal anterior displacement and reverse obliquity pattern ideal for closed treatment in a halothoracic vest or similar device.

Odontoid Fractures

Odontoid fractures are the most common C2 fracture. Anderson and D'Alonzo classified odontoid fractures into 3 types.⁵⁶ Type 1 fractures represent an avulsion fracture of the alar ligament and appear as an oblique fracture through the tip of odontoid. Type 2 fractures are the most common and occur at the junction of the dens with the C2 body. Type 3 fractures extend into the cancellous portion of the axis body. Treatment options include hard cervical collar, halo-vest, anterior odontoid screw fixation or posterior C1–2 arthrodesis. Treatment is based on fracture type, patient age, displacement (> 5 mm), angulation ($> 10^\circ$), comminution and integrity of the transverse ligament. Transverse ligament disruption necessitates C1–C2 arthrodesis.

Type 1 fractures are considered stable and can be managed with a hard cervical collar for 6 weeks. Occipito-cervical dislocation should be ruled out as at least one of the alar ligaments is always injured. Undisplaced type 3 fractures have a high potential for union (given their location in cancellous bone) and should be immobilized in a halo-vest or a hard cervical collar for 12 weeks.⁵⁷

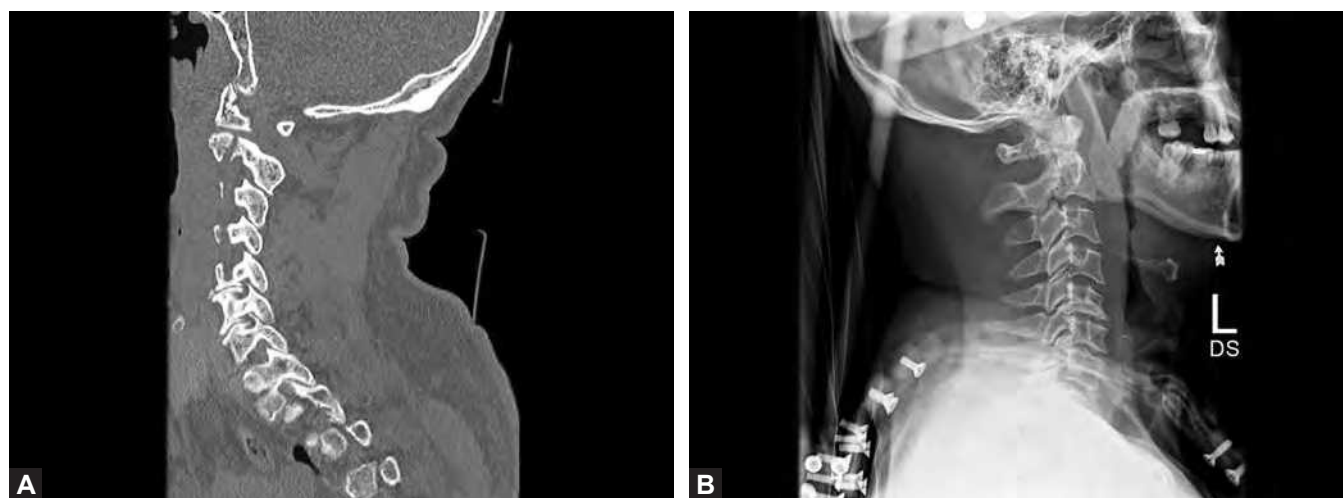
Type 2 fractures have a high potential for nonunion (because of their location in a hypovascular watershed area) and have attracted a great deal of controversy regarding their management. In the elderly, nondisplaced type 2 fractures (typically caused by low energy injuries) can be managed with a hard cervical collar for 12 weeks.^{58–61} Even though nonunion rates with this method may be very high (especially in the elderly), a stable asymptomatic fibrous

union is usually achieved.^{18,60} In this population, even movement at the pseudoarthrosis does not often lead to an adverse clinical outcome.⁶¹ Halo-vest application in elderly is poorly tolerated and has been shown to be associated with significantly increased morbidity and mortality.^{18–20}

Nondisplaced type 2 fractures in a young patient may be treated with immobilization in a halo-vest or hard cervical collar for 12 weeks.⁶² Comminuted and reverse obliquity pattern fractures are also generally treated with a halo-vest, as anterior fixation is generally not feasible and posterior fusion carries significant morbidity in loss of motion (Figs. 51.4A and B). Displaced or angulated fractures may be reduced with halo traction, followed by immobilization in a halo-vest. Frequent radiological follow-up is necessary as the reduction can be unstable and transition to surgical management may be required. The nonunion rates for displaced type 2 fractures are higher when external immobilization is used, but the advantages of preserving motion at C1–C2 are obvious.²⁶

C1–C2 Subluxation

Rotatory subluxations of C1 on C2 are high energy injuries in adults, but can occur more frequently in children. Fielding and Hawkins classified rotatory C1–C2 subluxation into 4 types.⁶³ Type 1 has no anterior displacement, Type 2 has anterior displacement less than 5 mm (mild transverse ligament deficiency), Type 3 has anterior displacement > 5 mm (transverse ligament is ruptured) and Type 4 is a posterior dislocation.



Figs. 51.5A and B: Type II Hangman's fracture treated with external stabilization in a halo-thoracic vest.

Type 1 and 2 injuries are differentiated from more severe forms because the transverse ligament remains intact.⁶³ As a result, these can be treated with closed reduction (with transoral digital manipulation if needed) with a halo ring and traction and can be converted to a halo-vest or even a hard cervical collar for definitive management for 10–12 weeks. Irreducible dislocations as well as more severe injuries are not amenable to closed treatment.

Other C2 Fractures

Unilateral or bilateral fractures of the C2 lamina, articular facets, pars or pedicle are usually included in traumatic spondylolisthesis of axis (Hangman's fracture). This injury pattern is essentially an injury to the C2–C3 motion segment. Effendi et al. classified these injuries into 3 types.⁶⁴ Type 1 has < 3 mm displacement and no angulation (C2–C3 disc, anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL) are intact), Type 2 has > 3 mm displacement and some angulation (C2–C3 disc, ALL or PLL are injured) and in Type 3, the C2–C3 facet joints are dislocated. These injuries are usually hyperextension injuries, but Levine and Edwards described a Type 2A flexion-distraction injury, associated with acute angulation in flexion, but no displacement, of C2 with respect to C3.³³ These fractures are markedly unstable in distraction, so it is critical to recognize this pattern and differentiate it from other Type 2 injuries which can often be reduced by closed methods.

Generally, Type 1 fractures are managed with halo-vest or hard cervical collar immobilization for 6–8 weeks.²⁵ Most Type 2 fractures can be managed with a halo-vest

or hard cervical collar for 8–12 weeks with spontaneous fusion across C2–3 disc in many cases²⁵ (Figs. 51.5A and B). Displaced Type 2 fractures can be reduced in halo traction followed by conversion to halo-vest for definitive management.^{27,65} Most Type 2A and Type 3 fractures are not amenable to closed treatment beyond reduction and require open stabilization.^{25,27,65}

SUBAXIAL CERVICAL SPINE FRACTURES

Assessing Stability for Closed Treatment

Traumatic fractures of the subaxial cervical spine range from very stable, benign injuries to frank clinical instability resulting in early neurologic injury. A number of anatomic and mechanistic classifications identify characteristics of the unstable spine, which also characterizes the appropriateness of closed treatment.^{66–68} The Subaxial Cervical Spine Injury Classification System (SLIC) includes three domains (morphology, neurologic status, and discoligamentous complex injury) and assigns a score on which surgical stabilization may be justified.⁶⁷ More traditional approaches infer instability from radiographic criteria,⁶⁸ and it has been suggested that these criteria may also be used to justify surgical stabilization over closed management.⁶⁹ In either case, it is important to recognize that despite a great deal of clinical experience and biomechanical evaluation, little consensus exists among experts regarding optimal management of many subaxial

cervical injuries,^{38,70,71} and a clear understanding of the principles and limitations of closed cervical management is required.

Cervical Spine Dislocation/Subluxation

Reduction

Subaxial cervical dislocations may be both reduced and potentially stabilized by closed methods. Historically, some authors had advocated stabilization in situ for dislocated facets, but due to poor outcomes, this technique has been abandoned.³⁰ Reduction is considered mandatory to both restore alignment and if necessary, decompress the neural elements. The use of closed traction or manual reduction to restore alignment remains controversial, largely due to a series of case reports describing iatrogenic neurologic injury.^{34,37} It has traditionally been felt that these neurologic injuries are the result of displacement of large disc or endplate fragments in to the spinal canal during the reduction.³⁴ Complex, difficult, or delayed reductions are thought to increase this risk.³⁷ In order to assess the risk of this complication, many authors have stressed the importance of obtaining an emergent MRI prior to closed reduction to rule out any substantial disc material behind the superior vertebral body of the dislocated level.^{34,38} Experts continue to vary, however, in both their use and interpretation of MRI,⁷⁰ and more recent imaging studies have failed to support the claim that disc material commonly herniates in to the canal.⁷² Despite the controversy, the use of closed reduction techniques as described earlier in this chapter and by other authors^{28,29} remains a viable and popular step in the management of cervical dislocations with or without fracture, but must be used with caution. In certain circumstances, MRI is required:

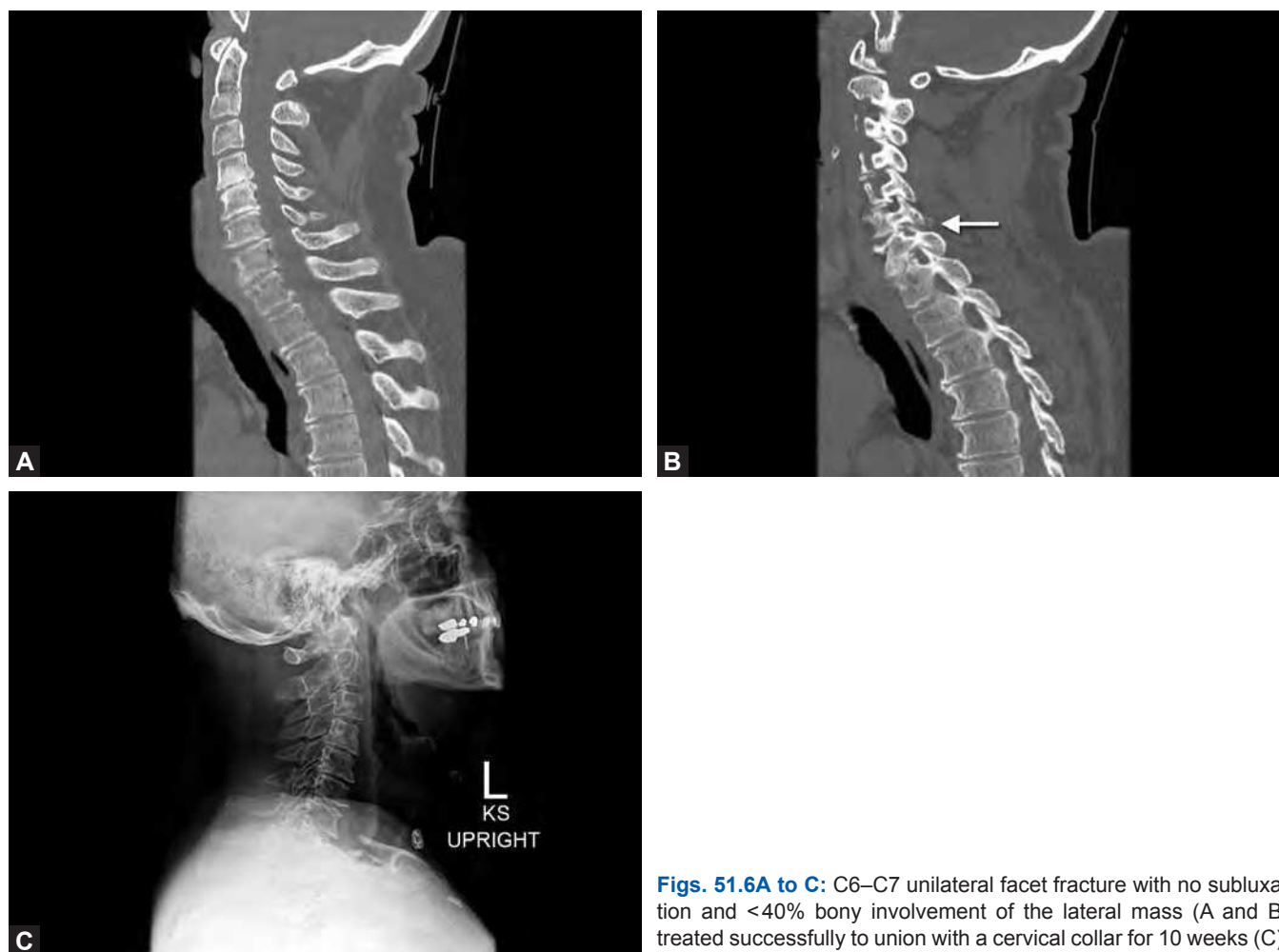
- Obtunded or unexaminable patients either with or without neurologic injury
- Dislocations in which posterior-only surgery is planned with reduction under anesthetic.

In other settings, closed reduction may be performed either in the awake patient or anesthetized patient at the discretion of the consultant after review of the available imaging. Close neurologic monitoring or immediate surgical decompression and stabilization is mandatory, regardless of the treatment algorithm used and the availability of MRI.

Stabilization and Definitive Treatment

The use of cervical orthoses for both subluxed and dislocated facet fractures as well as undisplaced injuries also remains controversial. Historically, closed immobilization has been used for subaxial fractures or dislocations following reduction even with neural element injury.^{29,30,73} In current practice, these injuries are nearly always treated surgically with both internal fixation as well as decompression of the neural elements. In cases without neural element injury, several studies have assessed radiographic predictors of stability using both CT as well as MRI scanning. It is presumed that injuries without hallmarks of instability on initial imaging are less likely to progress to healing in an unfavorable position and are also less likely to deform over time, potentially creating secondary neurologic injury and neck pain.^{41,74,75}

In general terms, in patients with more substantial bony injury, even if there is no initial malalignment of the spinal column, instability is considered more likely. For example, the linear extent of the fracture in an initially undisplaced injury has been shown to be predictive of late instability, particularly if the fracture involves greater than 40% of the lateral mass.⁷⁶ This measurement can easily be assessed on imaging that is universally obtained in patients with a cervical injury. Fractures involving both the superior articular process of the inferior vertebra and the inferior articular process of the superior vertebra (i.e. a “kissing” fracture) are also inherently less stable and are not appropriate for closed treatment.⁷⁷ Fractures involving a “floating” joint with fractures of both the lateral mass and pedicle also respond poorly to closed treatment resulting in a high incidence of ongoing radiculopathy.⁷⁸ Several studies have also demonstrated increased instability and higher failure rates with closed treatment for lateral mass fractures that are associated with vertebral body compression or burst fractures, and those associated with initial kyphosis on initial radiographs.^{41,75,77,79} In addition to plain X-ray and CT scans, MRI may be used to assess ligamentous disruption of the major stabilizers including the anterior and posterior longitudinal ligaments, the ligamentum flavum, facet capsules and interspinous ligaments. Disruption of three or more these structures has been found to be predictive of late subluxation in initially well-aligned fractures.⁸⁰ This latter finding is supported by expert opinion in the SLIC system.⁶⁷ Perhaps more intuitively, those injuries with initial subluxation or facet malalignment (perched or



Figs. 51.6A to C: C6–C7 unilateral facet fracture with no subluxation and <40% bony involvement of the lateral mass (A and B) treated successfully to union with a cervical collar for 10 weeks (C).

locked, especially bilaterally) are also less likely to remain in a stable position with the use of closed techniques alone.^{39,41,74}

Historically, closed treatment using a halo-thoracic vest was met with mixed results, largely because of the inclusion of patients with radiographic signs of more severe instability. Stable healing was the result in between 17–70% with most reports including some residual neck pain or symptomatic stiffness.^{39,41,73–75,79,81,82} Increased kyphosis or displacement was associated with increased pain or disability.^{73,75,82} More recent work has demonstrated acceptable outcomes in patients with unilateral fractures treated in halo-vest compared to early surgery, albeit with slightly worse outcomes in terms of bodily pain on standardized quality-of-life outcomes.⁸¹

Despite these limitations, however, closed treatment of particular unilateral facet fractures remains a viable

option for certain fractures without the worrisome radiographic parameters discussed previously (Figs. 51.6A to C). As discussed earlier in this chapter, either halo-vest or hard collar immobilization are reasonable choices, both offering relative advantages and disadvantages. Due to its invasive nature, the use of the halo-vest may carry additional risks including pin site infection and skin breakdown. In addition, it can have relatively poor control of some mid-subaxial injuries in control of flexion and extension due to the snaking phenomenon.⁷ Cervical hard collars are easier to apply and maintain, but lack the overall control of axial compression and overall neck motion afforded by a more rigid construct.⁴ Regardless of the method of immobilization, close follow-up is required. Numerous studies have outlined successful treatment with surgery during the first 2–4 weeks after injury if closed reduction fails to maintain alignment.^{29,30,77,79,82} Routine radiographs and clinical

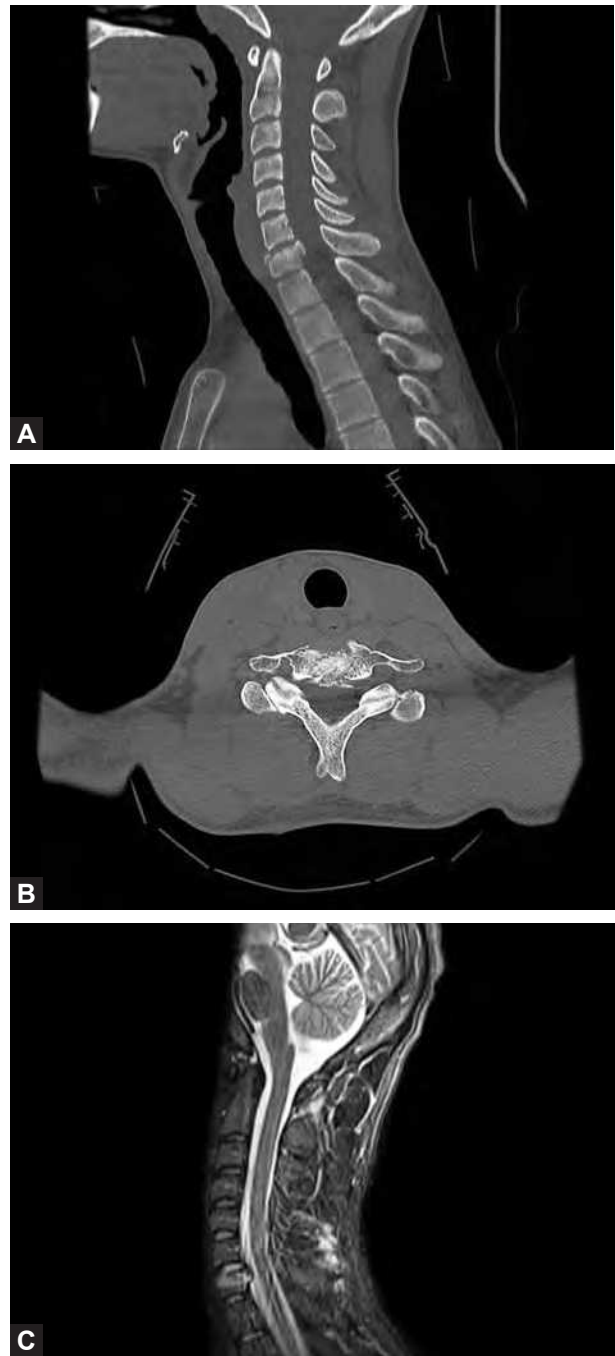
examinations should be performed at least once during the first 2–3 weeks after injury to ensure that alignment is maintained and neurologic function is preserved. If closed treatment fails, open reduction after this time may become progressively more difficult and neurologic recovery (if a deficit exists) is less likely.²⁹ Duration of immobilization is generally 10–12 weeks, although considerable variation exists in the literature.^{29,30,39,41,77,79,81,82}

CERVICAL BURST AND FLEXION TEARDROP FRACTURES

The cervical spine is a relatively rare location for burst fractures, relative to the lower thoracic and upper lumbar spine.⁸³ The SLIC system defines a separate category in the morphology subcomponent for burst fractures, and these injuries are also outlined in the Allen classification, generally as vertical compression injuries.^{66,67} Flexion “teardrop” fractures are generally thought to represent a related flexion-compression mechanism with injury to the facet or posterior soft tissues, but without distraction of the posterior elements.⁶⁶

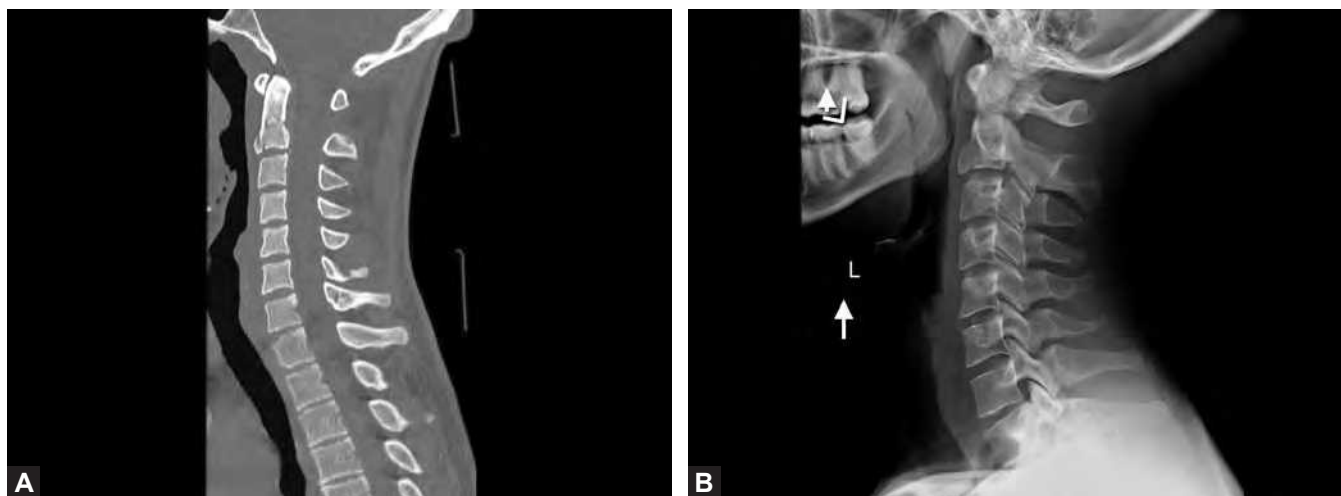
In terms of treatment, these injury patterns are often grouped together. In older studies, halothoracic vest treatment was met with a very high failure rate for maintenance of reduction as well as patient outcomes.^{29,39,41,74} Unfortunately, these older studies included a mix of fracture types that are sometimes not well described. More recent literature comparing surgical and closed treatment, however, also favors surgery in most cases. Halo traction followed by treatment in the halothoracic vest for 12–14 weeks is effective for preventing neurologic deterioration in most cases, but results in higher degrees of kyphosis.^{40,84} No difference, however, has been shown in patient-centered outcomes despite this radiographic difference.

In certain fracture types, however, closed treatment is a reasonable option, particularly where little chance of post-traumatic kyphosis exists. This situation is rarely the case when flexion-distraction or “teardrop” fractures are present; however, in the SLIC system, a burst fracture, even with complete disruption of the discoligamentous complex, does not score highly enough to justify routine surgical intervention unless there is subsequent neurologic compromise. If possible, closed treatment avoids the sometimes morbid stabilization and fusion of two intervertebral levels with a corpectomy or multi-level posterior stabilization. Pure burst fractures with intact posterior elements may be managed using a hard collar or halothoracic vest, depending on the degree of comminution and



Figs. 51.7A to C: C7 burst fracture with no significant kyphosis on computed tomography (A and B) and minimal posterior ligamentous disruption on magnetic resonance imaging scan (C). This pattern is ideal for closed treatment in either a hard-collar or halothoracic vest for 10–12 weeks.

other patient characteristics (Figs. 51.7A to C). Close radiographic follow-up is required to ensure that alignment is maintained and neurologic symptoms do not develop.^{40,41}



Figs. 51.8A and B: C2 extension teardrop fracture (A) treated to union (B) in a hard collar for 10 weeks.

Cervical Extension or Extension Teardrop Fractures

Unlike vertical compression or flexion-distraction injuries, extension injuries tend to be more stable and are more amenable to closed treatment. The determination of the mechanism of fracture can be difficult, and is based on the clinical history, associated injuries (such as scalp or facial trauma), and imaging. In the absence of ankylosing conditions, most extension injuries such as the C2 teardrop fracture may be adequately immobilized with a cervical hard collar for 8–12 weeks and union is generally expected (Figs. 51.8A and B). Neurologic complications are rare, and although limited literature is available on these injuries, available reports describe little, if any, late complications such as instability, pain, or functional impairment.^{85,86}

Spinous Process Avulsion (Clay-Shoveller's Fracture)

Fractures of the spinous process of the lower cervical (and upper thoracic) spine are colloquially known as Clay-Shoveller's fractures, after their description in a working population in western Australia.⁸⁷ These fractures are related to muscular avulsions of the spinous process and do not affect the overall stability or function of the spinal column. Kyphosis is rarely seen⁸⁷ even in neglected cases. Closed management is recommended, and the use of a hard or soft collar may help to limit pain during the early phase of recovery.

KEY POINTS

- Hard collars as well as invasive and noninvasive cervicothoracic orthoses each have relative benefits and drawbacks for immobilization of the cervical spine after injury. Treating physicians should be aware of the potential for complications from any orthotic.
- Cervical traction is a useful tool for reduction of many injuries including facet dislocations as well as upper cervical injuries. It should be avoided in patients with distraction type injuries.
- Upper cervical injuries should be carefully assessed for signs of relative stability before choosing closed management. Ligamentous as well as bony stability needs to be considered.
- Closed traction for subaxial cervical spine injuries is generally safe and effective, but in rare cases can be complicated by serious neurologic sequelae. There is no consensus algorithm for safe traction, but strong consideration should be given to emergent MR imaging before reduction.
- Definitive management of subaxial cervical injuries such as facet fractures and vertical compression fractures is often effective where relative stability is expected and there is little chance of progressive subluxation or angular deformity.

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Cervical Spine Injuries in the Athlete: Return-to-Play Criteria

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Snapshot

- » Epidemiology
- » Anatomy/Mechanisms of Injury

- » Return-to-Play Criteria

INTRODUCTION

There are approximately 12,500 new cases of spinal cord injury (SCI) per year, with 8.4% of the total causes of SCI from sports injuries (compared with 39.1% from motor vehicle collisions).¹ While SCI is not as common as extremity injuries among athletes, these injuries are concerning because of the tremendous potential for morbidity and mortality. There is a large spectrum of cervical spine injuries, ranging from injuries that are largely clinically insignificant with no neurologic sequelae to devastating injuries that render the cervical spine unstable and cause dense quadriparesis. The difficulty and controversy arises when making decisions as to when an athlete can return to play (RTP) after a cervical spine injury. Medicolegal issues must also be considered, since the surgeon is making a recommendation that could result in catastrophic injury to the athlete who is prematurely or inappropriately returned to play. Unfortunately, no definitive guidelines exist due to the lack of high-quality evidence. Here, we present our expert opinion, supported by evidence when available, on RTP criteria for common injuries to the cervical spine sustained during sport.

EPIDEMIOLOGY

Since 2010, sporting injuries were the fourth most common cause of SCI in the United States after motor vehicle collisions, falls, and acts of violence.¹ Injuries to the cervical spine occur most frequently in athletes participating in

contact sports, and in the United States, particularly during American Football.^{2,3} Other sports that place athletes at high risk include ice hockey,⁴ wrestling,⁵ and rugby⁶; however, other sports during which SCI has been described include mountain biking,⁷ skiing or snowboarding,⁸ diving,⁹ and horseback riding.¹⁰ Certain injuries occur with alarming frequency such as burners/stingers, with 50% or more of college American football players reporting experiencing this injury.^{11,12} Other injuries are more rare but can have more dire consequences.

ANATOMY/MECHANISMS OF INJURY

Stingers/Burners

Stingers or burners are injuries that are characterized by weakness, paresthesias, and radiating pain that involves only a single extremity. The athlete typically complains of burning or tingling in an arm that is associated with weakness after an acute injury. Most episodes are transient, lasting from seconds to minutes; however, occasionally symptoms can be persistent for days to weeks. Symptoms classically are in a dermatomal or myotomal distribution if the injury is due to nerve root compression, although multiple levels are often involved with an injury to the plexus, which can cause a more confusing clinical picture. C5 and C6 are the most commonly involved levels, with resultant weakness in shoulder abduction (deltoid) and elbow flexion and forearm supination (biceps). There are multiple mechanisms that can cause a burner or stinger.

1. Traction injury to the brachial plexus that occurs with ipsilateral shoulder depression with side bending of the neck to the contralateral side.
2. Compression injury to a cervical nerve root that can occur with neck extension and contralateral rotation, or ipsilateral side bending.
3. Direct compression of the plexus at Erb's point, which typically occurs during American Football when the plexus gets compressed between the shoulder pads and the superior-medial scapula.¹³

Transient Quadripareisis

Transient quadripareisis is an injury characterized by paresthesias or weakness in more than one extremity, which is in contrast to a stinger or burner that only involves a single extremity. Torg et al.¹⁴ reported the incidence in college football players to be approximately 1.3 in 10,000 athletes. Symptoms can range from only mild paresthesias to a dense quadripareisis. The duration of symptoms is usually brief lasting only 10–15 minutes, but athletes can have residual symptoms lasting up to 36 hours. The mechanism of injury, as opposed to a burner or stinger, is typically forced neck hyperextension, causing spinal cord compression between the inferior aspect of the cephalad vertebral body and the superior edge of the lamina of the caudad level. Hyperflexion can similarly also result in cord compression. Patients with underlying cervical canal stenosis, either congenital or acquired, are thought to be at higher risk and have more frequent recurrences of transient quadripareisis.¹⁵ Other athletes at risk include those with any structural abnormalities of the cervical spine, including cervical kyphosis, Klippel-Feil abnormalities, cervical instability, and/or intervertebral disc protrusion or herniation.

Cervical Fractures

Cervical spine fractures represent a heterogeneous population of injuries, which can range from those that are essentially clinically insignificant (spinous process avulsion fractures) to those that can cause catastrophic neurological deficits (fracture/dislocations). Each injury must be evaluated on an individual basis as each has a unique mechanism and must be treated with the patient's underlying anatomy and sport-specific needs in mind.

Spinous Process Fractures

Spinous process fractures usually occur as a result of a strong contraction of the trapezius or rhomboid musculature, or a hyperflexion mechanism, causing an avulsion

fracture of the posterior elements. Less commonly fractures can result from a direct blow to the spinous process.

Compression Fractures and Burst Fractures

Compression and burst fractures occur from an axial load on the head with the neck in variable degrees of flexion. Compression fractures generally occur in lower energy mechanisms although this is not the rule. The major differentiating factor between burst fractures and compression fractures is that the posterior cortex of the vertebral body is disrupted in burst fractures, thus placing the cord at risk due to possible retropulsion of bony fragments.

Flexion-Distract Injuries

Flexion-distract mechanisms of injury can significantly destabilize the spine with resultant SCI and neurological deficit. These injuries occur with forced cervical flexion after axial loading of an already flexed neck. This results in an injury pattern with tensile failure of the posterior elements and subsequent fracture of the vertebral body, often with the production of a "teardrop fragment" involving the antero-inferior vertebral body. Although less common, facet dislocation without a concomitant articular process fracture can result in significant neural compression and injury as the intact articular processes act as a block to spontaneous reduction and subsequent canal decompression.

"Spear Tackler's Spine"

Spear tackler's spine represents a constellation of findings that includes vertebral body anomalies consistent with previous trauma, canal stenosis, reversal of the normal cervical lordosis, and a confirmed history of tackling while leading with the head ("spearing").¹⁶ These elements have been associated with a very high risk for neurological injury.

Stenosis

Congenital or acquired spinal stenosis involving the cervical spine can place athletes at higher risk for neurological injury due to decreased space available for the spinal cord. There have been various radiographic methods described for the detection and quantification of stenosis. One of the more frequently used methods described by Pavlov et al.¹⁷ is the Torg ratio, which compares the width of the vertebral body with the width of the spinal canal on a lateral cervical radiograph, with a ratio of <0.8 being used to

define cervical stenosis. Torg et al.¹⁸ examined American football players from high school to professional level that had suffered an episode of transient neuropraxia to determine whether there was any relationship to stenosis and found that a Torg ratio cutoff of 0.8 had high sensitivity (93%) for transient neuropraxia but an extremely low positive predictive value (0.2%). Another study in professional American football athletes confirmed the low positive predictive value of the Torg ratio for the presence of true spinal stenosis precluding its use as a screening tool for stenosis.¹⁹ Plain radiographs ignore the contribution of the soft tissue components that frequently cause stenosis, such as intervertebral disc protrusions, facet capsule hypertrophy, or ligamentous hypertrophy. Rather than defining stenosis by the canal dimensions, a more “functional” definition of stenosis may be that when the cerebrospinal fluid signal surrounding the cord is lost on magnetic resonance imaging (MRI) or computed tomographic (CT) myelography.²⁰

Klippel–Feil

Klippel–Feil abnormalities are characterized by congenital fusion of adjacent vertebral bodies. The fusion may only involve two levels or may be more complex with multiple adjacent segments involved or even noncontiguous segments. Restrictions on ability to participate in contact sports depend on which levels and how many levels are involved in the abnormal fusion. Furthermore, Klippel–Feil can commonly be associated with cardiac, renal, or other organ system abnormalities, which can further preclude participation in sports.

Cervical Disc Herniation

Cervical disc herniation is a career-threatening problem that can cause neck pain, radiculopathy, and/or myelopathy. It results in functional stenosis that cannot be appreciated with plain radiography alone, and depending on the extent and associated symptoms it can present a barrier to play. Players in sports that involve repetitive axial loading of the head and neck, such as American football, have been shown to have a higher incidence of cervical disc disease compared with the general population.²¹ Front-row rugby players also represent a high-risk population.²²

RETURN-TO-PLAY CRITERIA

Many published criteria exist for RTP; however, none of these are based on high-level evidence given the rarity of

the injuries. Almost universally these criteria are based on small retrospective case series and the educated opinion of experts in the field.

Stingers/Burners

Return-to-play decision making after a stinger should consider the severity of the symptoms, the number of episodes, and the timing of the episodes. After the first stinger or a second stinger occurring in a different season, the athlete can RTP immediately after the symptoms are resolved, and he or she has full, painless neck range of motion (ROM). If symptoms are persistent or do not completely resolve, the athlete should have further workup including imaging studies. After the second stinger occurring in the same season, the athlete should sit out the remainder of the game but can RTP the following game if symptoms have completely resolved and he or she has full, painless neck ROM. After the third stinger occurring in the same season, the athlete should sit out the remainder of the game regardless of severity or duration of symptoms. If symptoms are severe, the player should sit the remainder of the season. Furthermore, the athlete should have a full clinical and radiographic evaluation for the underlying etiology (e.g. congenital stenosis). Strong consideration should be given to restricting the athlete from contact sports if he or she has persistent or severe symptoms.

Transient Quadripareisis

Any athlete with an episode of transient quadripareisis warrants a full radiographic and clinical evaluation with X-rays and an MRI to evaluate for cord injury, stenosis, and/or underlying cord parenchymal abnormality (cord signal change). If there is no stenosis or cord parenchymal injury or abnormality, the athlete can RTP once he or she is asymptomatic and has full, painless neck ROM. If there is mild or moderate stenosis without evidence of cord injury and the athlete quickly recovers pain-free neck ROM, there is a relative contraindication to return to contact sports. The decision on whether the athlete ultimately can RTP is complex and must be made after a careful discussion between the athlete and his or her physician, in addition to any other involved parties. Important factors to consider are the severity and duration of the episode, the type of sport and the position played, and the level of play (high school, collegiate, and professional). If the athlete has severe stenosis or if there has been more than a single episode of transient quadripareisis, there is an absolute contraindication to return to contact sports.

For most spine practitioners, this scenario involves a student athlete who is accompanied by his or her parent. In such cases, we tend to have a stricter RTP criterion because of the medico-legal implications. The parents must be present and notified of the potential for permanent injury. Although there is scant evidence that transient quadriplegia is a predictor of permanent quadriplegia in the future, we make it clear to the parents that the absence of proof is not proof of the safety of returning to play. On the contrary, the argument for returning to play is that the overwhelming majority of those who suffer a permanent SCI have never had an episode of transient quadriplegia. Nonetheless, we explain that while the risk of an athlete suffering an SCI is low, if it happens to their child, it is 100% and likely permanent. Medicolegally, it is imperative that the parents are present and that all clinic visits are well documented. Even with a thorough discussion regarding the risks of returning to play, a lawsuit is highly likely if the surgeon “clears” the patient to return and the child subsequently suffers a permanent injury.

Cervical Fractures

In cases of cervical fractures, there is an absolute contraindication to RTP for a minimum of 10–12 weeks after the injury to allow for bony healing. While the athlete may be able to train after 6–8 weeks, depending on the fracture and the fixation, contact sports can result in refracture, even with stable flexion-extension views. We recommend obtaining a CT scan to document healed fracture, followed by maximal flexion-extension radiographs to document stability prior to allowing RTP. The RTP criteria depend on the type of fracture and the subsequent operative or nonoperative treatment. The function of the cervical spine is threefold: (1) to provide structural support for the soft tissues of the head and neck, (2) to allow for positioning of the head in three-dimensional space, and (3) to protect the spinal cord and cervical nerve roots. If the traumatic injury or subsequent treatment compromises any of these functions then the athlete has an absolute contraindication to return to contact sports. With this in mind, absolute contraindications for RTP include atlanto-occipital fusion, odontoid abnormalities, C1-C2 instability or fixed rotatory deformity, spear tackler’s spine, dynamic subaxial instability (>3.5 mm translation or $>11^\circ$ angulation), sagittal malalignment, trauma-induced canal compromise from retropulsed bony canal fragments or a herniated disc, persistent neurologic deficit, or >2 fused motion segments.²³

Relative contraindications to RTP include healed upper cervical spine fractures (nondisplaced Jefferson’s fractures, healed type I and type II odontoid fractures, healed lateral mass fractures of C2), healed minimally displaced compression fractures, healed fracture of the posterior elements (excluding spinous process fractures), or a healed one- or two-level anterior or posterior cervical fusion.²³ This is provided that the patient is pain free, has full ROM, and has no neurological deficits. Injuries that present no contraindication to RTP include healed spinous process avulsion fractures or healed nondisplaced subaxial fractures once the athlete has painless full ROM, and has regained strength and coordination in the head and neck.

We counsel players that these recommendations are not based on scientific evidence or large-scale clinical trials. However, they have been in use for >15 years and are generally agreed upon by experts in the field.

Stenosis

Given that contact athletes are not routinely screened for cervical stenosis, the diagnosis is usually made after the athlete has suffered a stinger with prolonged symptoms, had an episode of transient quadriparesis, or sustained another injury for which cervical spine imaging was obtained. In an athlete in whom the diagnosis of cervical stenosis is truly made incidentally with no neck symptoms and no neurological deficit, there is no contraindication to RTP. However, in any patient being worked up for neck pain, or radiculopathy with imaging findings consistent with either congenital or acquired stenosis, they have a relative contraindication to RTP. We believe that myelopathy due to congenital stenosis and not a large disc herniation that can be surgically treated is a contraindication to RTP. Many professional football players have a narrowed canal. We inform them that the presence of stenosis puts the athlete at a higher risk for neurological injury with any force imparted to the cervical spine. Any decision to return to sport must only be made after a full and informed discussion with the athlete, parents, and any other involved parties.

Cervical Disc Herniation

As described previously, cervical disc herniations may cause functional spinal stenosis and can place the athlete at higher risk of neurological injury following trauma involving the head and neck. Therefore, any athlete with

a known history of cervical disc herniation must be evaluated and examined carefully prior to allowing the patient to participate in contact sports. Furthermore, the athlete must be counseled that he or she has an increased risk of neurological injury with trauma compared with someone without a disc herniation. If a patient has a truly asymptomatic disc herniation, with no signs of radiculopathy or myelopathy on physical examination, he or she can RTP if he or she has painless cervical spine ROM. If a patient has a symptomatic disc herniation with neck pain, decreased ROM, radiculopathy, or myelopathy he or she should not be allowed to participate in contact sports.

After Anterior Cervical Discectomy and Fusion

Single-level cervical spine surgery for disc herniation in the general population has almost universally good to excellent outcomes; however, the demands placed on a fused cervical spine by athletes are quite different from that of the general population. Especially in American football, where numerous high-energy loads are transmitted to the head and neck each game, athletes are at high risk for cervical spine injury especially if they have had prior operative intervention. There is some data available on the outcomes of RTP for National Football League American (NFL) football players after cervical spine surgery. Hsu²⁴ showed that 72% of players successfully returned to play for an average of 2.8 years after single-level cervical spine surgery. However, because the data collection was based on publicly available information, only 60% of these players were confirmed to have had an anterior cervical discectomy and fusion (ACDF). More recently, Maroon et al.²⁵ reported their series of 15 NFL football players who underwent single-level ACDF and found that 13 of 15 were able to RTP at a mean of 6 months postoperatively. The RTP duration for those who retired after full participation ranged from 1 to 3 years. An analysis of 19 professional rugby players who underwent ACDF for symptomatic disc herniation showed that 68% returned to play at the same level of competition, with the majority returning by 6 months.²² Two players had recurrent symptoms with one being forced to retire. Although sparse, the published data support that athletes in contact sports can successfully RTP after a one- or two-level ACDF once the fusion has healed and they demonstrate painless, full neck ROM. Because of the increased lever arm and subsequent higher risk of neurological injury, an athlete should be restricted

from return to contact sports after a three- or more level ACDF. It is imperative to ensure that athletes have achieved a solid arthrodesis based on CT imaging prior to allowing them to RTP.

Cervical Disc Arthroplasty

To our knowledge, there is no published data on RTP after cervical disc arthroplasty. However, Tumialan et al.²⁶ did report on return to active duty in military personnel, a patient population that places high physiological stress and demand on their cervical spines similar to athletes. In their series, 12 patients (seven Navy SEALs, one marine, one landing craft air cushion engineer, and three high-ranking officers) underwent cervical arthroplasty, all of whom returned to unrestricted full duty by 3 months. The activities they were able to participate in by 3 months included parachute jumping, high-impact water entries from helicopters, diving, and long-distance runs while carrying a load. The arthroplasty group was compared with a similar cohort who underwent a single-level ACDF and found that the average time to unrestricted full duty for the arthroplasty group was shorter than that for the fusion group (10.3 weeks vs. 16.5 weeks, $p = 0.008$); however, this difference likely reflects the fact that fewer postoperative restrictions were placed on the arthroplasty group compared with the arthrodesis group rather than truly faster recovery. In this military series, their algorithm allowed for return to full unrestricted duty by 3 months. They allowed nonimpact training as soon after surgery as they were comfortable to do so, typically within the first month. In the second month, they were allowed to do light-impact activities and light weight training. Provided they remained asymptomatic, they were allowed to progress to high-impact training by the third month. It is our opinion that a single-level arthroplasty is as stable as an arthrodesis for most sports except high-impact sports such as American football.

Klippel-Feil

Klippel-Feil abnormalities are functionally similar to anterior interbody fusions and have similar barriers with regard to RTP. With one- or two-level Klippel-Feil abnormalities that do not involve the occipito-cervical junction or the C1-C2 articulation, there is no contraindication to RTP as long as the athlete has full, painless neck ROM. Athletes with fusions of three motion segments or greater should be restricted from participating in contact sports.

CONCLUSION

Cervical spine injuries are heterogeneous ranging from those with minimal to no sequelae on one end of the spectrum to complete quadriplegia on the other end of the spectrum. Each injury must be evaluated in the context of the athlete's unique cervical spine anatomy (i.e. patent canal vs. stenotic) with regard to the physical demands required for the athlete's particular sport and position. Stingers and burners are extremely common, and patients can typically RTP quickly after symptoms subside following a first-time event. Return to play is more variable and occurs at a lower rate following transient quadriplegia or ACDF. Ultimately, an individualized approach to each injury is necessary and must be carried out with the full informed consent of the athlete and all involved parties. Medicolegal issues must be kept in mind when making decisions.

KEY POINTS

- Stingers and burners are incredibly common in athletes and may be underreported. Athletes can RTP after a first episode once asymptomatic and have recovered full strength.
- Transient quadriplegia is a more serious injury and a careful workup should be performed to rule out intrathecal pathology or severe canal stenosis with prolonged symptoms.
- Athletes can successfully RTP after one- or two-level ACDF.
- All cervical spine injuries mandate an individualized approach for appropriate treatment and RTP assessment.

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Upper Cervical Spine Trauma

Christopher A Burks, Adam L Shimer

Snapshot

- » Anatomy
- » Epidemiology
- » Evaluation
- » Occipital Condyle Fractures
- » Occipitocervical Dissociation
- » Atlas Fractures
- » Transverse Ligament Rupture
- » Traumatic Rotatory Atlantoaxial Dislocation
- » Odontoid Fractures
- » Traumatic Spondylolisthesis of the Axis

INTRODUCTION

The upper cervical spine, or occipital-cervical junction (OCJ), includes the osseous, ligamentous, and neurovascular structures that extend from the occiput to C2. This is a very mobile functional segment, thus injuries are quite common as with other transitional spinal segments at the cervicothoracic and thoracolumbar junctions. The large moment arm produced by the cranium on the inherently unstable osseous structures is borne by specialized ligaments making this area particularly prone to injury. Due to the presence of vital neurovascular structures, injuries to the upper cervical spine can be fatal and are a common finding on autopsy of blunt trauma deaths.¹⁻⁴ Improvements in automobile safety and trauma care have increased survival of the inciting trauma, making diagnosis and management of the constellation of injuries to the OCJ increasingly more common. This chapter will describe the functional and surgical anatomy of the OCJ, the epidemiology, evaluation, and evidenced-based management of the following injuries to the OCJ: occipital condyle fractures, occipital-cervical dissociation, atlas fractures, traumatic atlanto-axial instability, odontoid fractures, and traumatic spondylolisthesis of the axis.

ANATOMY

The upper cervical spine is responsible for approximately 60% of the total axial rotation of the cervical spine, 40% of total flexion and extension, and 45% of overall cervical motion.^{5,6} The bony components include the occiput with its bilateral condyles, the atlas (C1), and the axis (C2) with its large cranial projection, the odontoid process. The associated capsulo-ligamentous structures are responsible for providing increased restraint and stability to this highly mobile area, thus protecting the brainstem and spinal cord. The unique osseoligamentous anatomy of the upper cervical spine is demonstrated in the spectrum of injuries unique to the area. A thorough understanding of this anatomy is paramount to the evaluation and treatment of upper cervical spine injuries.

There are two articulations between the occiput and atlas providing the bony support for the cranium on the axial skeleton. The oval-shaped occipital condyles articulate with the concave superior articular facets of C1 in a shallow ball and socket articulation. These paired joints are sloped $30 \pm 7^\circ$ in the coronal plane⁷ inferiorly toward the midline allowing for 20° – 30° of flexion and extension, 5° – 10° of lateral bending, but little to no axial rotation.⁸⁻¹⁰ The atlas and axis have four synovial articulations. The

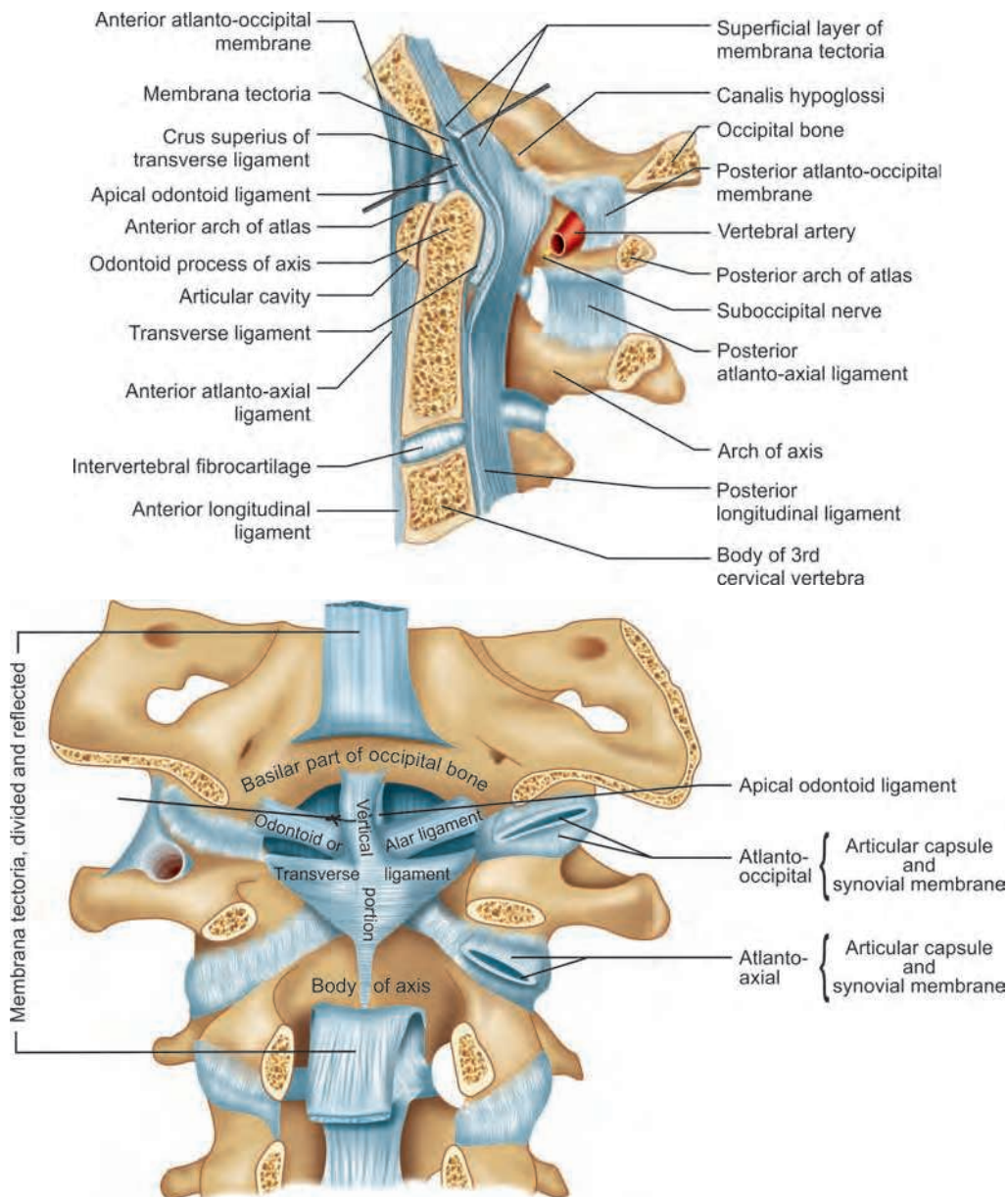


Fig. 53.1: Illustration depicting the bony and ligamentous anatomy of the upper cervical spine.

superior facets of C2 articulate bilaterally with the broad, shallow inferior facets of the atlas. The posterior aspect of the anterior arch of C1 articulates through a synovial joint with the anterior aspect of the odontoid process. There is a secondary synovial articulation between the posterior aspect of the odontoid process and the transverse atlantal ligament (TAL). Together, approximately 60% of the total axial rotation of the cervical spine occurs through these C1-C2 articulations. In this function, C1 serves as a washer between the occiput and C2, with ligamentous structures providing for controlled motion of C1 and C2.

There are many ligamentous structures associated with the upper cervical spine. The ligamentum flavum, ligamentum nuchae, and anterior and posterior longitudinal ligaments are analogous to, or continuations of, similar structures in the subaxial spine. Those structures unique to the upper cervical spine include the cruciform ligament, the alar ligaments, apical ligament, tectorial membrane, and the anterior and posterior atlanto-occipital membranes (Fig. 53.1).

The apical ligament lies in the space between the anterior atlanto-occipital membrane and the cruciform

ligament spanning from the tip of the odontoid to the anterior aspect of the foramen magnum. It has no specific role in stabilizing the OCJ. The anterior and posterior atlanto-occipital membranes span from the anterior and posterior aspects of C1, respectively to the foramen magnum defining its extent. The tectorial membrane is a broad expansion of the posterior longitudinal ligament that originates on the posterior body of C2 and inserts bilaterally on the anterolateral edge of the foramen magnum. Along its course it shares fibers to reinforce the lateral C1-C2 facet joint capsules. The exact function of the tectorial membrane is unknown. It has been hypothesized that it limits axial distraction of the OCJ, restrains flexion of the occiput-C1 articulation, and provides protection against compression of the thecal sac and spinal cord from the anteriorly located odontoid.¹¹⁻¹³

The most important ligamentous structures of the OCJ are the alar ligament and the transverse portion of the cruciform ligament. The paired alar ligaments originate on the dorsolateral surface of the odontoid and travel obliquely to insert on the lateral mass of C1 and the inferomedial occipital condyle. The alar ligaments help maintain the position of the odontoid relative to C1 and are the primary restraint to axial rotation of both the atlanto-occipital and atlantoaxial segments with some effects on lateral bending and flexion.^{11,12,14} They are slack in the neutral head position and during rotation the alar ligament on one side tightens allowing up to 90° of rotation to the contralateral side. Sectioning of a single-sided alar ligament in cadaveric specimens resulted in increased flexion and contralateral lateral bending at occiput-C1 and increased flexion, extension, and rotatory instability at C1-C2.^{8,9} Sectioning of the second ligament resulted in little change. The cruciform ligament is composed of both a vertical component and a transverse component. The vertical component spans from the posterior body of C2 to the clivus superiorly. The transverse component, known as the TAL, attaches to the medial aspect of the C1 lateral mass traveling posterior to the odontoid process holding the odontoid to the anterior arch of C1. It serves to limit flexion, extension, translation, and bending of the C1-C2 articulation while allowing for rotation. At 6–7 mm in thickness and height, it is the largest ligament of the OCJ, the primary stabilizer of C1¹⁵ and, with a load to failure of 350 N, is 66% stronger than the alar ligaments.⁵

■ EPIDEMIOLOGY

A large meta-analysis demonstrated an overall prevalence of cervical spine injuries of 3.7% in all blunt trauma

patients and 7.7% in obtunded patients, with 41.9% of cervical spine injuries exhibiting instability.¹⁶ Upper cervical spine trauma occurs in a bimodal distribution with a preponderance of injuries occurring in pediatric patients and in those over 60 years of age. Children under age 7 with cervical spine injuries are most likely to have been injured in a motor vehicle crash (MVC) and 74–80% of the injuries are at the OCJ.^{17,18} Adolescents aged 8–15 with cervical spine injuries are equally likely to be injured in an MVC as they are playing sports, with 47% of cervical spine injuries occurring at the OCJ. The mortality rate for these injuries is between 7% and 25% with the higher values including those with concomitant closed head injury. In comparison to children, fractures of the upper cervical spine in those over 60 years of age are more likely to be caused by low energy falls (45–100%) than high energy MVC. Nearly 70% of all cervical spine fractures in this age group occur at the OCJ, with up to 60% of the injuries occurring to the odontoid process.¹⁹⁻²¹

■ EVALUATION

The evaluation of the blunt trauma patient should proceed as always according to Advanced Trauma Life Support protocol to minimize the risk of failure to identify significant injuries and to stabilize the hemodynamically unstable patient. Care should be taken to maintain strict spinal precautions and bracing until the patient can be examined both clinically and with imaging. Failure to appropriately diagnose upper cervical spine injuries in a timely fashion can result in precipitous neurologic deterioration and death.^{22,23}

Imaging

Historically, plain radiography of the cervical spine, including anteroposterior, lateral, and open mouth odontoid views has been considered an integral part of the evaluation of the blunt trauma patient. Most injuries of the OCJ can be appreciated on plain radiography; however, they are inadequate to fully characterize the OCJ secondary to projectional and rotational issues.^{24,25} One series demonstrated an 8% rate of occipital condyle, atlas, and axis fractures that were not apparent on lateral radiographs.²⁴ Increases in the prevertebral soft tissue shadow may indicate an injury. The anterior soft tissue shadow on lateral radiography should be approximately 6 mm at C2 and 20 mm at C6. Increases from these values should prompt the use of more advanced imaging modalities.

Computed tomography (CT) of the cervical spine with axial, sagittal, and coronal three-dimensional (3D) reconstructions have largely replaced plain radiography in the evaluation of the upper cervical spine in blunt trauma patients due to the high sensitivity, specificity, and cost efficacy in detecting injuries.²⁶⁻²⁸ Extensive normative data has been produced to assist in detecting subtle instability even in the absence of fractures.^{29,30} Raza et al. showed that normal CT scans of the cervical spine have a negative predictive value of 99.7% for clinically significant cervical spine injury even in obtunded patients.³¹ Purely ligamentous injuries of the cervical spine are quite rare, and most can be detected by CT or plain radiography and do not require the use of magnetic resonance imaging (MRI).^{32,33}

Magnetic resonance imaging is the ideal imaging modality for evaluating the soft tissue structures of the OCJ. Though multiple studies have shown CT to consistently rule out clinically significant cervical spine injuries including instability, there remains a utility for characterizing the soft tissue structures in combined bony and soft tissue injuries of the OCJ when purely bony injuries could be treated with an orthosis or halo-vest. Waiting for upright plain radiography or MRI in obtunded patients increased the length of time spent in cervical collar with spinal precautions in obtunded trauma patients by 2.4 days and did not detect any previously undiagnosed injuries in patients with negative multidetector CT scan.³³ A fluoroscopically visualized, surgeon-controlled, axial traction test has been proposed for evaluating for instability related to ligamentous injury but has not been validated.³⁴ In addition, flexion and extension radiographs have been used to evaluate those with negative radiography and CT imaging, though studies have shown no increased detection rates.³⁵

■ OCCIPITAL CONDYLE FRACTURES

Fractures of the occipital condyle were first described by Bell in 1817.³⁶ They are most commonly unilateral and are found in 1–3% of all OCJ injuries.³⁷ They are routinely associated with closed head injury and cranial nerve injuries due to the proximity of cranial nerves VI, IX, X, XI, XII.³⁸ Fractures of the occipital condyle are often stable injuries and may be treated nonoperatively with cervical collars, noninvasive cervicothoracic orthoses, or halo-vest immobilization. Evaluation of ligamentous integrity is the key to determining treatment strategy.

Saturnus first attempted to classify occipital condyle fractures by force vector, utilizing autopsies to identify six distinct fracture patterns.³⁹ This system was refined by

Anderson and Montesano in 1988 when they proposed classifying the fractures into three distinct morphological types.⁴⁰ Type I fractures are comminuted fractures of the occipital condyle, are most commonly unilateral, and are the result of an axial load. Type II fractures are fractures of the base of skull, may be bilateral, and are often the result of a direct blow to the head causing the condyle to shear. They may leave the condyle free floating from the base of the skull. Type III fractures are avulsion fractures of the inferomedial occipital condyle involving the attachment of the alar ligament. They are the result of combined lateral bending and rotation forces. The determination of stability of the occiput-atlas articulation is the key to management. Bilateral injuries are more likely to be unstable.

The majority of isolated occipital condyle fractures without malalignment or associated atlanto-occipital instability can be treated in a cervical collar or more restrictive orthosis such as a Minerva or sternal occipital mandibular immobilizer (SOMI) though studies in healthy volunteers have showed minimal difference in motion restriction between the specific orthoses.⁴¹ Nonoperative management of stable fractures is successful for healing of fractures in >90% without risk of secondary dislocation.⁴² Nonoperatively treated OC fractures are associated with mild to moderate neck disability as measured by the neck disability index regardless of gender; patients aged 40–60 tend to do slightly worse.^{42,43} In a retrospective review from a single level I trauma center, Maserati et al. reported on the successful nonoperative treatment of all occipital condyle fractures without associated atlanto-occipital instability or malalignment in a cervical collar or SOMI brace.⁴⁴

The decision for operative management is based on stability and alignment. Type II injuries with displacement of the atlanto-occipital articulation should be treated with reduction and halo-vest application under fluoroscopy. Occasionally, occipitocervical fusion may be required if closed reduction cannot be achieved. Type III injuries with instability and/or displacement should be treated with occipitocervical fusion.

■ OCCIPITOCERVICAL DISSOCIATION

Occipitocervical dissociation is associated with high mortality rates.³ Improvements in trauma care and diagnostic imaging have increased both the rate of detection and the survivability of these injuries. They are frequently associated with craniofacial and closed head injuries.⁴⁵ Atlanto-occipital injuries are more common in the pedi-

ric population due to more horizontally oriented atlanto-occipital facets and their increased head to body weight ratio. These relatively uncommon, highly unstable injuries are most commonly caused by distraction and hyperflexion or extension in high energy blunt force trauma.

Traynelis proposed a classification of atlanto-occipital dislocations based on the direction of displacement.⁴⁶ Type I injuries exhibit anterior displacement of the occiput relative to the cervical spine. Type II injuries exhibit distraction of the atlanto-occipital joints in which <2 mm distraction is considered normal. Type III injuries are dorsal displacement and type IV injuries are complex. While this classification describes the appearance of the injuries it does not provide prognostic information or treatment guidance.

Several methods have been developed for detecting these injuries on plain radiographs and many have been adapted to nondistorted sagittal reconstructions of CTs. Harris lines include the basion-axis interval (BAI) and basion-dens interval (BDI) that are both <12 mm in normal subjects.²⁵ The Wackenheim clival line runs tangential to the posterior cortex of the clivus and should pass within 1–2 mm of the posterior tip of the dens and is indicative of a reduced OCJ (Fig. 53.2).⁴⁷ Powers Ratio is based on the relationship between the basion and the posterior arch of the atlas compared with the relationship between the opisthion and the anterior arch of the atlas.⁴⁸ A ratio of 0.77 is considered normal and >1 abnormal, indicating anterior dislocation; however, utilization may produce false negatives in type II or III injuries (Fig. 53.3).⁴⁹ The revised occi-

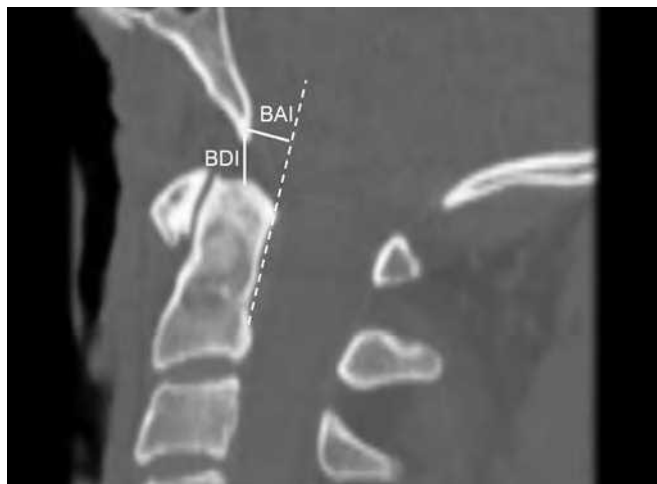


Fig. 53.2: Representation of the basion-axis interval (BAI) and the basion-dens interval (BDI). Values >12 mm should raise suspicion for atlanto-occipital dissociation.

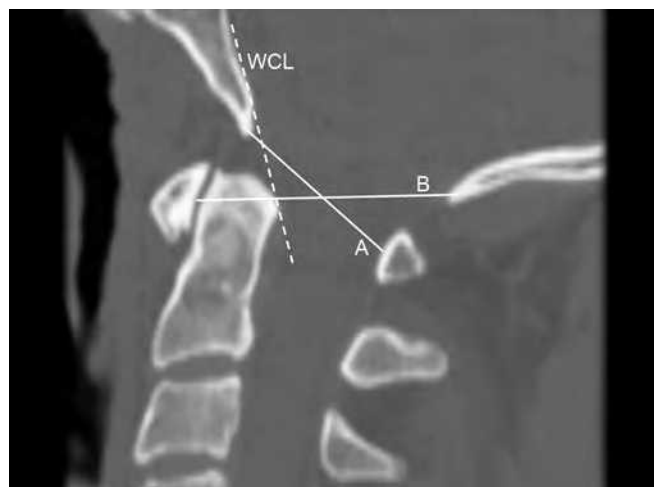
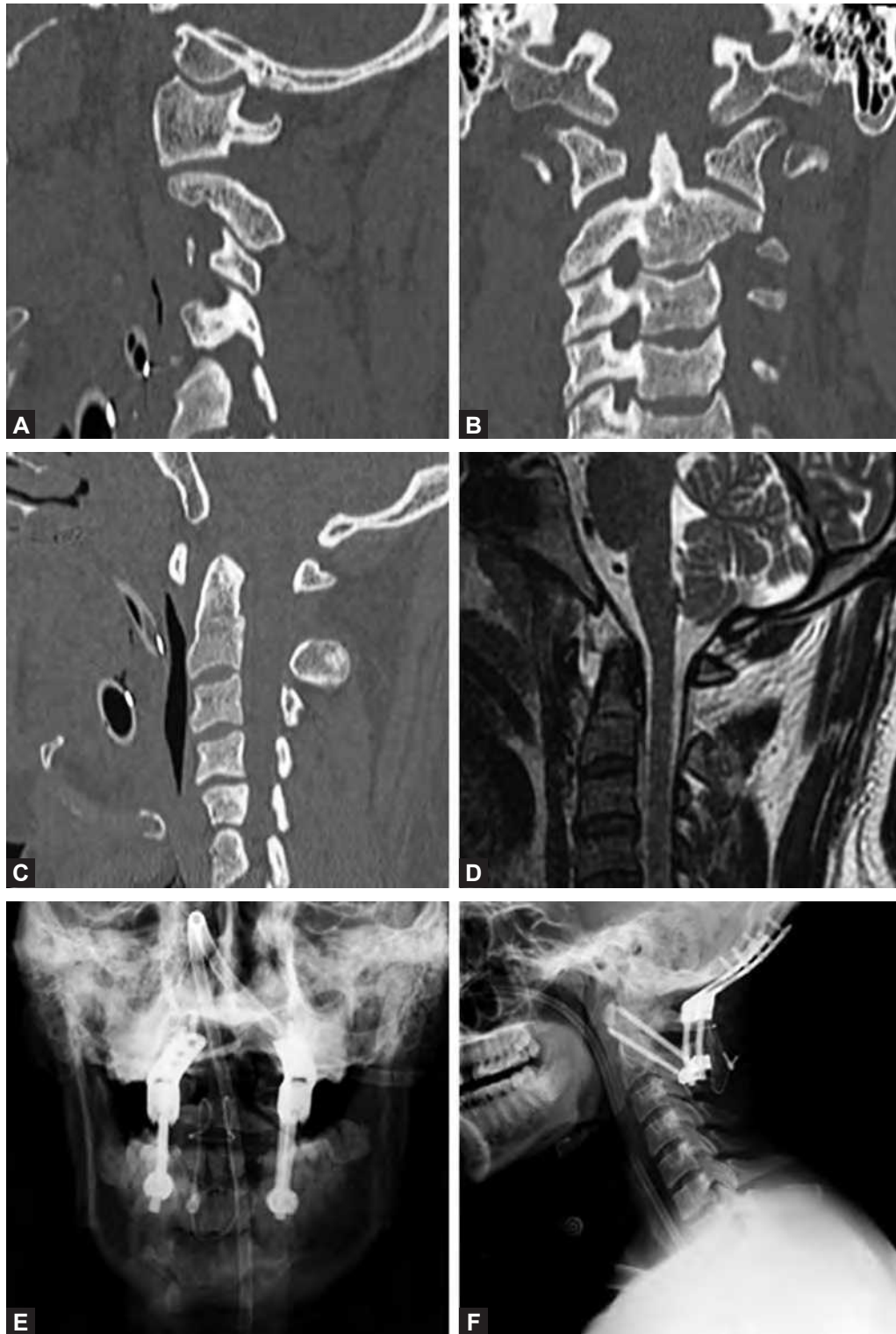


Fig. 53.3: Representation of the Wackenheim Clival Line (WCL) that should pass within 1–2 mm of the posterior tip of the dens, indicating a reduce occipitocervical junction. Powers Ratio (A/B) can be used to assess for an anterior atlanto-occipital dislocation. A ratio of 0.77 is normal with >1 being abnormal.

pital condyle-C1 interval measures the maximum distance between the occipital condyle and the lateral mass of C1 on a mid-sagittal CT view, and has been shown to have excellent inter-rater reliability.⁵⁰ It is considered abnormal if >2.5 mm and careful consideration of advanced imaging should be considered. Prior studies have shown significant uniformity in the congruency of the atlanto-occipital articulation with a mean separation of 0.6 mm.³⁰

The Harborview classification of occipitocervical dislocation as proposed by Bellabarba et al. includes both primary atlanto-occipital distraction, as well as C1-C2 distraction, C1-C2 translation, and combined patterns.⁴⁵ It classifies these injuries according to stability and subsequent treatment strategy by assessing CT, MRI, and if indicated traction radiography. The BAI and BDI are the originally described diagnostic criteria. Type 1 injuries have negative CT findings, positive MRI findings of non-displaced ligament injuries and can be treated with a cervical orthosis. Type 2 injuries have normal CT findings, positive MRI findings of ligament injuries, and a positive traction test, which indicates spontaneous reduction of the dislocation but underlying instability. They can be treated successfully with halo-vest if reduction can be maintained, though late displacement may require posterior fusion. Type 3 injuries demonstrate gross instability on both CT and MRI. They should be treated initially with immediate halo-vest application and definitively with posterior cervical arthrodesis to include the occiput if necessary (Figs. 53.4A to F). Caution must be exercised with the use



Figs. 53.4A to F: A 22-year-old man sustained an unstable craniocervical dissociation without fracture in an auto versus pedestrian accident. (A, B, and C) Axial and sagittal computed tomography cuts demonstrating incongruity of the occiput—C1 articulation, widening of the occiput-C1 and C1-C2 facets, and increased atlanto-dens interval (ADI), respectively. (D) T2-weighted sagittal magnetic resonance imaging sequence demonstrating increased ADI. (E and F) Open mouth and lateral radiographs following occiput to C2 fusion with C1-C2 transarticular screw-occipital plate construct and Gallie graft wiring.

of cervical collars in these dissociative conditions as they have been shown to cause distraction of the upper cervical spine.^{45,51}

■ ATLAS FRACTURES

Atlas (C1) fractures account for approximately 5% of all cervical spine injuries and a quarter of all injuries to the atlantoaxial complex.⁵² Jefferson first described atlas fractures in 1921. The eponymous Jefferson fracture is characterized by bilateral fractures in the anterior and posterior arches of the C1 ring and constitutes the most common C1 injury pattern. It is often the result of an axial load with or without lateral bending and is highly associated with head injury and/or other cervical spine injuries.^{52,53} Other C1 injury patterns include isolated anterior or posterior arch fractures, transverse process fractures, or lateral mass fractures.

The most important factor guiding treatment of C1 fractures is an assessment of stability. The two most common radiographic measurements utilized are the lateral mass overhang and atlanto-dens interval (ADI). Combined lateral mass overhang on the open mouth view should be <7 mm.⁵⁴ Widening >7 mm indicates transverse ligament rupture and instability necessitating stabilization. An ADI >3 mm in adults and >5 mm in children is also indicative of a transverse ligament rupture.⁵⁵ The integrity of the TAL can also be assessed directly with MRI.

The majority of isolated nondisplaced C1 fractures can be safely treated with a rigid collar.⁵⁶ Jefferson burst type fractures with mild displacement can be treated in a cervicothoracic orthosis such as a SOMI or Minerva or with halo-vest immobilization. Initial closed reduction with traction and halo-vest application for 3 months can be considered for fractures with <7 mm displacement with flexion-extension radiographs obtained upon halo removal. If instability is present at that time then C1-C2 arthrodesis should be performed (Figs. 53.5A to F). Multiple complications have been reported with long-term use of halo-vest immobilization including loss of reduction with cranial settling, pin-site infection, intracranial abscess, and pulmonary compromise.⁵⁷ Recently, immediate surgical stabilization has been the preferred method of treatment to avoid the morbidity of long-term halo-vest immobilization.

The most commonly used methods of surgical stabilization include C1-C2 screw and rod constructs, as initially described by Harms,⁵⁸ and C1-C2 transarticular screw fixation, as initially described by Grob and Magerl.⁵⁹

Posterior wiring can be included if the posterior arch is intact. These procedures require traction to reduce the spread of the lateral masses prior to instrumentation and can be technically demanding. Occasionally, occiput to C2 fusion is required if O-C1 instability is present or anatomic considerations such as lateral mass fractures preclude C1 lateral mass fixation. Due to the morbidity of loss of motion at the C1-C2 segment, motions preserving direct C1 ring osteosynthesis procedures have been developed. Transoral reduction of the lateral masses with anterior fixation has been reported but is technically difficult and carries a high risk of infection.^{60,61} Motion preserving posterior procedures have been reported as well involving closed reduction with traction and subsequent lateral mass screw placement connected by a transverse rod.⁶² Koller et al. demonstrated in a biomechanical study that primary C1 ring osteosynthesis does not result in any increased C1-C2 instability even in cases of known transverse ligament rupture.⁶³

■ TRANSVERSE LIGAMENT RUPTURE

The transverse ligament rupture (TAL) is the primary stabilizer of the atlanto-odontoid articulation. As with most ligaments in the body, primary healing is unlikely with injury. Integrity of the TAL is the largest determinant of stability in atlas fractures and subsequently stability of the atlantoaxial complex. While rare, isolated injuries are possible and can be diagnosed by plain radiographs or CT, using the ADI as described above, or by assessment with MRI. Occasionally flexion-extension radiographs of the upper cervical spine may be required.

Ruptures of the TAL were classified by Dickman et al. into two types based on the location of the rupture.⁶⁴ Intrasubstance ruptures are subdivided into midportion (Type 1a) versus periosteal (Type 1b) ruptures. Rupture associated with avulsion fractures are subdivided based on the presence of a comminuted (Type 2a) or intact (Type 2b) C1 lateral mass. Type 1 injuries with static or dynamic instability should be treated with atlantoaxial fusion. Options for C1-C2 fusion are anterior screw fixation, posterior instrumentation with segmental screws, C1-C2 transarticular screws, and posterior C1-C2 wiring with autograft.

Historically, C1-C2 posterior wiring as described by Brooks or Gallie was the primary means of obtaining C1-C2 arthrodesis. C1-C2 posterior wiring alone requires the use of a halo-vest postoperatively, has a high rate of nonunion,



Figs. 53.5A to F: This patient sustained a Jefferson fracture in a motorcycle accident. (A) Axial computed tomography (CT) scan at C1 shows burst fracture of C1 with minimal displacement and likely avulsion fracture of transverse atlantal ligament. (B) Sagittal CT scan shows atlanto-dens interval within normal limits. (C) Upright open mouth and (D) Lateral radiographs in cervical orthosis demonstrates C1-C2 instability. (E and F) Cervical radiographs approximately 2 years status post-C1-C2 posterior instrumented fusion.

and is less biomechanically stable than constructs using screws; however, it has been shown to be an efficacious adjuvant to improve both fusion rates and stability.^{65,66} Either C1-C2 transarticular screws or C1 lateral mass, C2 pedicle or pars screw-rod constructs may be used. Transarticular screws place the vertebral artery more at risk particularly in the setting of a high riding vertebral artery. Naderi et al. demonstrated in a cadaveric biomechanical study that transarticular screw constructs were superior to posterior cable grafting with respect to lateral bending and axial rotation, but posterior cable grafting provided better control of flexion and extension.⁶⁷ The strongest construct was posterior cable-graft with bilateral transarticular screws. Melcher et al. demonstrated that posterior screw rod constructs were biomechanically equivalent to transarticular screws in a cadaver model.⁶⁸ Transarticular screw placement may not be possible for a number of reasons, including: an anomalous medial course of the vertebral artery present in 20% of the population, incongruity of the atlantoaxial joints, and severe thoracic kyphosis precluding appropriate starting point and approximately 65° screw trajectory.⁶⁹⁻⁷¹ Due to the significant anatomic variability of C2 and aberrant course of vertebral artery, C2 pedicle screws may not always be safely possible. In cases in which the anatomy limits placement of bilateral C2 pedicle screws, a construct using a unilateral C2 pedicle screw with a contralateral short pars screw is a viable option and compares favorably with a bilateral C2 pedicle screw construct.⁷² Fixation in C2 with the use of crossed transaminar screws has also been shown to compare favorably to C2 pedicle screws.⁷³

■ TRAUMATIC ROTATORY ATLANTOAXIAL DISLOCATION

Rotatory atlantoaxial subluxation or dislocation is often atraumatic and is well described in the pediatric population and in association with Down's syndrome, Marfan's syndrome, inflammatory arthritides, and Grisel's syndrome. Traumatic atlantoaxial dislocation or subluxation without fracture, however, is an uncommon clinical entity. It was first described in 1969 by Haralson and is often the result of a motor vehicle accident.⁷⁴ Patients will typically present with pain and/or torticollis. Plain radiography may indicate asymmetry of the lateral masses on open mouth view or increased ADI on the lateral. Often CT is required to diagnose and 3D volumetric reconstructions are especially helpful in detecting subtle rotational malalignment and in verifying reduction. Cadaveric- and MRI imaging-based

studies have demonstrated ruptured atlantoaxial facet capsules with subsequent failure of the alar ligaments to be the likely pathologic cause.^{75,76}

The most commonly used classification system was described by Fielding and Hawkins and is based on the direction of rotation and displacement.⁷⁷ Type I is purely rotatory with the odontoid as a pivot point and can occur without ligament rupture. Type II is rotatory with the lateral mass as a pivot point and usually is associated with a transverse ligament rupture resulting in an increased ADI. Types III and IV are anterior or posterior dislocation of the atlas.

Closed reduction with skeletal traction via cranial tongs is the treatment of choice in acutely diagnosed injuries. Stable reductions can be treated in a hard cervical collar for 8–12 weeks. Those with difficult closed reductions or subtle instability should be treated with a halo-vest. Unreducible dislocations require open reduction and C1-C2 arthrodesis. Even in patients with successful, stable closed reductions, range of motion is likely to be reduced and they may have persistent occipital neuralgia.⁷⁸

■ ODONTOID FRACTURES

Fractures of the odontoid process of C2 account for >40% of all C2 fractures, 10–15% of all cervical spine fractures, and are the most common fracture of the upper cervical spine in those over 65 years of age.⁷⁹ These injuries occur most commonly in young males following high energy trauma and in the elderly following ground level falls. While they can occur as a result of a number of biomechanical mechanisms, the most common etiology in the elderly is hyperextension in fall as a result of a posteriorly directed blow to the head. These injuries can be diagnosed on open mouth and lateral radiographs but nondisplaced injuries may require thin-cut CT images for diagnosis.

Odontoid fractures were classified by Anderson and D'Alonzo into three types based on the location of the fracture line.⁸⁰ Type I fractures occur at the tip of the odontoid, above the TAL, and are a result of an alar ligament avulsion. They are stable injuries that can be treated in a hard cervical collar. Type II fractures occur at the waist of the odontoid in the area covered by the TAL. Type III fractures extend into the body of C2. Grauer et al. modified the type II fractures based on the orientation of the fracture line in order to stratify treatment options.⁸¹ Type IIa fractures are nondisplaced. Type IIb injuries exhibit a fracture line running obliquely from anterior-superior to posterior-inferior. Type IIc fractures are comminuted or have fracture lines running anterior-inferior to posterior-superior.

Type I fractures that are stable can be treated in a cervical collar, however, if occipitocervical instability is present then arthrodesis is required. Type III fractures are amenable to nonoperative treatment due to the large bony surface area for healing to occur; however, they are unstable injuries and should be treated in a cervicothoracic orthosis or halo-vest. Nonunion or inability to maintain alignment are indications for C1-C2 arthrodesis.

Type II fractures are unstable injuries and must be treated accordingly. Due to the vascular watershed in this area of the odontoid, nonunion rates are approximately 30%.⁸² Risk factors for nonunion are age > 50, displacement > 6 mm, angulation > 10°, and residual displacement of >2 mm following halo-vest application.^{83,84} In young patients, these injuries can be treated in a halo-vest if alignment can be maintained; otherwise they are treated with instrumentation (Figs. 53.6A to F). This is especially true for nondisplaced (type IIa) injuries. In the acute setting, type IIb injuries can be surgically treated with an anterior odontoid screw placement, with healing rates reported as high as 96%,⁸⁵ or via posterior C1-C2 instrumented fusion. Anterior screw fixation is advantageous in this select subset of injuries as it can preserve motion at C1-C2. Anterior screw fixation should be undertaken cautiously in elderly patients as complication rates are high. Scheyerer et al. reported nonunions in 13 of 17 elderly patients treated with anterior fixation compared to a nonunion in 1 of 16 treated with posterior C1-C2 arthrodesis.⁸⁶ Vasudevan et al. reported high rates of postoperative pneumonia (30%) and dysphagia (43%) requiring supplemental feeding tube placement in a cohort of patients over 65 years of age treated with anterior screw fixation.⁸⁷ Type IIc injuries may be treated with either halo-vest or posterior C1-C2 fusion, but due to the orientation of the fracture planes are not amenable to anterior screw fixation.

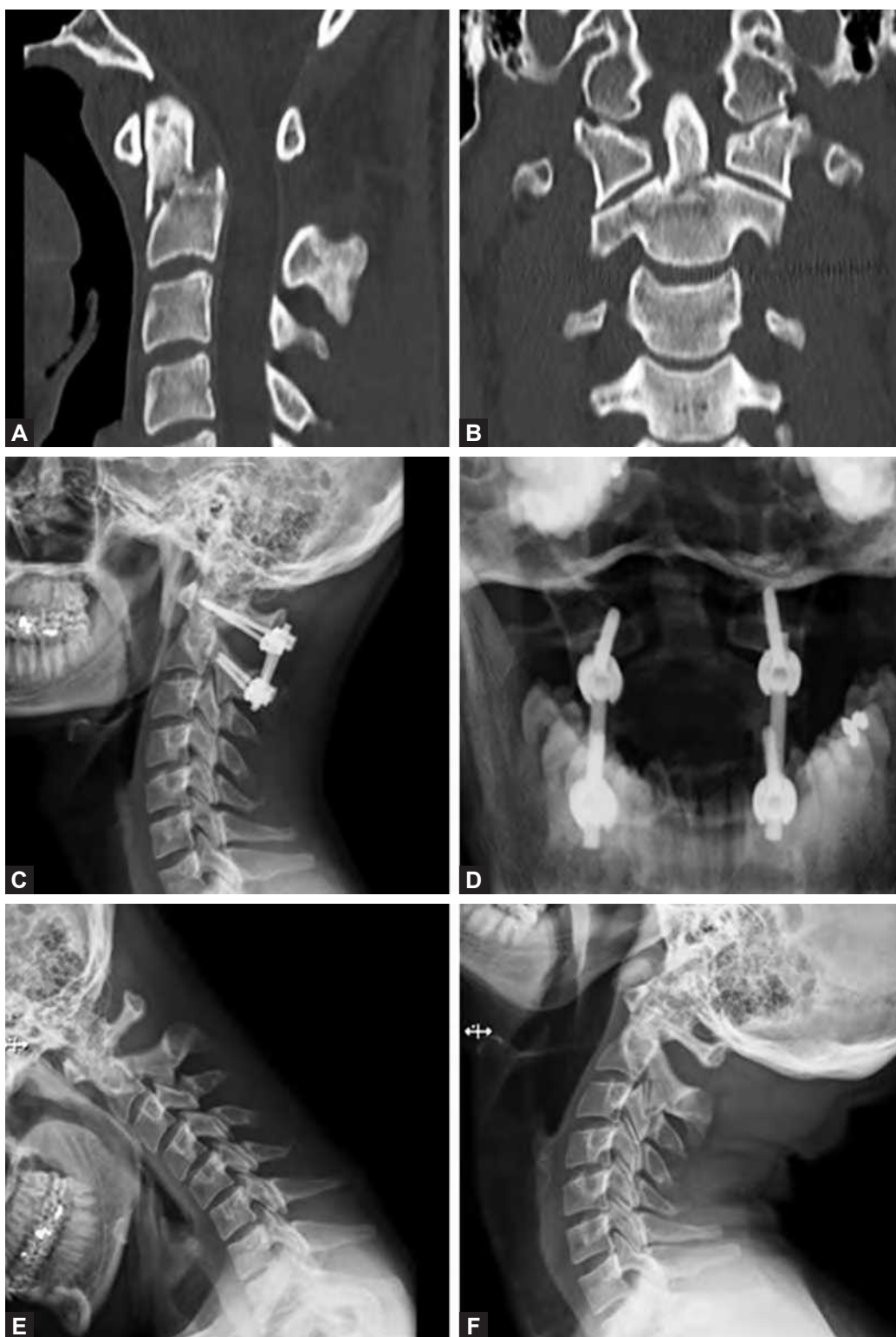
Odontoid fractures in the elderly are predominantly type II and are associated with significant morbidity and an elevated risk of mortality similar to that of hip fractures. There is significant controversy over the best method for treating these injuries. Mortality rates have been reported to be between 10% and 57% in this group.⁸⁸ Tashjian et al. demonstrated a 42% mortality rate in elderly patients treated with a halo-vest and high rates of pneumonia due to the restrictive nature of a properly fitted vest.⁸⁹ The use of halo-vests should be avoided in elderly patients due to the significant impact on mortality. Treatment should either be a collar immobilization or posterior C1-C2 arthro-

desis utilizing the techniques described elsewhere in this chapter. Chapman et al. demonstrated in a cohort of 322 patients with type II odontoid fractures that surgical treatment significantly improved 30-day mortality with a trend towards improved long-term survival compared with nonoperative treatment.⁹⁰ Woods et al. found similar data with respect to 30-day mortality, but no difference between operative and nonoperative survival rates at 1 and 5 years.⁹¹ Mortality was most significantly related to the Charlson Comorbidity Index regardless of treatment. Prospective multicenter studies have shown that there is decreased mortality and improved functional outcomes in elderly patients undergoing surgical treatment. In those patients treated nonoperatively, 22% ultimately required surgery secondary to fracture nonunion.^{92,93} Interestingly, patients with nonunion did not report worse outcomes compared with those who achieved union at 12 months.⁹⁰ In patients with acceptable comorbidities, the trend is currently towards surgical stabilization.

■ TRAUMATIC SPONDYLOLISTHESIS OF THE AXIS

Traumatic spondylolisthesis of the axis, known colloquially as a Hangman's fracture, is a fracture through the neural arch of C2. They were initially classified by Effendi et al. with subsequent modification by Levine and Edwards.^{94,95} Type I injuries are bilateral fractures of the pars interarticularis as a result of hyperextension and axial load with <3 mm of translation and no angulation. Type II injuries are displaced (>3 mm) and angulated bipedicular fractures with discoligamentous injury as a result of hyperextension followed immediately by flexion. They may appear similar to Type I injuries on supine radiographs or CT, but will displace on upright radiographs as a result of the disc injury. Type IIA injuries have significant disc and posterior longitudinal ligament injury and will have significant angulation with minimal translation and may be associated with other cervical spine injuries as a result of a flexion-distraction force (Figs. 53.7A to D). Type III injuries include C2/3 facet dislocations and are highly unstable.

Type I injuries are stable and may be treated with a cervical orthosis for 12 weeks. Type III injuries commonly are unreducible by closed means and require surgical reduction via a posterior approach with subsequent C2-C3 or C1-C3 posterior instrumentation and arthrodesis. There is controversy surrounding the treatment of Type II and IIA



Figs. 53.6A to F: An 18-year-old man sustained a type 2 odontoid fracture that failed attempted closed reduction with a halo-vest. (A and B) Axial and sagittal computed tomography cuts demonstrating a Type IIc odontoid fracture with 8 mm of anterior displacement. (C and D) Lateral and open mouth radiographs following C1-C2 screw-rod construct placement without fusion. (E and F) Flexion and extension radiographs following removal of instrumentation after fracture healed.



Figs. 53.7A to D: This patient sustained an occipitocervical dislocation with associated type IIA Hangman's fracture. Initial treatment was in a halo-vest without reduction due to hemodynamic instability precluding immediate surgical stabilization. (A) Sagittal computed tomography cut demonstrating anterior occipital subluxation and Hangman's fracture (arrow). (B) Sagittal T2-weighted magnetic resonance imaging demonstrating C2/3 disc disruption (arrow) and spinal cord signal changes. (C and D) Anteroposterior and lateral radiographs demonstrating occiput to C3 posterior instrumented fusion.

injuries. Vaccaro et al. reported on a series of 31 patients with Type II or IIA injuries who were successfully treated with early reduction and halo immobilization.⁹⁶ Six out of 27 patients in the Type II cohort required revision reduction in traction due to delayed fusion and all were noted to have had an initial angulation of $>12^\circ$. Treatment in a halo may result in healing in a nonanatomic position leading some to advocate for surgical osteosynthesis or segmental fusion.⁹⁷ Excellent results have been shown with C2-C3 anterior discectomy and fusion as well as posterior C2-C3 instrumented fusion^{98,99} with a biomechanical study

showing them to offer similar stability.¹⁰⁰ Primary osteosynthesis of a type II fracture has been reported with direct repair with C2 pars screws.¹⁰¹ In cases where fixation cannot be achieved across the fracture at C2, extension to C1 may be required.

SUMMARY

Upper cervical spine injuries are common injuries that are increasing in numbers as trauma care and automobile safety improves. These injuries can be missed, especially

in purely ligamentous injuries, with the potential for neurologic deterioration. The use of thin slice multidetector CT as the gold standard for evaluation in blunt trauma patients has increased the detection of these injuries. Care must still be taken to evaluate for ligamentous injury. The algorithm for surgical versus nonsurgical management is based on displacement, stability, and the status of the soft tissue restraints.

KEY POINTS

- Upper cervical spine injuries are frequently diagnosed on a delayed basis with potentially severe neurologic sequelae.
- Multiple imaging studies, including radiographs, CT, and/or MRI may be required to fully evaluate the occipitocervical junction with thin slice CT best evaluating the bony structures and MRI evaluating the soft tissue structures.
- Nonoperative treatment is often the preferred method of treatment of osseous injuries without ligamentous instability such as most occipital condyle fractures, atlas fractures, traumatic spondylolisthesis of the axis, and odontoid fractures.
- Operative treatment is often reserved for injuries with purely ligamentous or combined osseoligamentous injuries with significant static or dynamic instability.
- The choice of fixation method in C1 and especially C2 must be based on the individual patient's anatomy due to the variability of both bony anatomy and vertebral artery course.
- Operative treatment of Type II odontoid fractures in the elderly is controversial; however, it is associated with fewer nonunions, better functional outcomes, and a lower 30-day mortality compared to treatment in a rigid cervical collar. Halo-vests should be avoided in the elderly.

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Nonoperative and Operative Treatment of Subaxial Cervical Spine Trauma Including Dislocations

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Snapshot

- » Epidemiology
- » Anatomy
- » Diagnosis
- » Classification
- » Management of Selected Injuries

EPIDEMIOLOGY

Subaxial cervical spine injuries account for 2–3% of all reported blunt trauma and two-thirds of cervical fractures and dislocations.^{1,2} Hu et al.² reported an annual incidence of 64 per 100,000 and identified a bimodal age distribution in young males and elderly females. The etiology of most subaxial trauma includes motor vehicle and transport incidents particularly in the younger population and accidental falls in the elderly.² Injuries to C6 and C7 contribute to the majority of lower cervical spine trauma¹ with most cases not resulting in neurologic or spinal cord injury (SCI).^{2,3}

The burden of cervical spine fractures has significant implications on lifetime disability, mortality, and health-care cost and utilization. Baaj et al.³ reported a 74% increase in hospitalizations following cervical spine fractures in the United States over a 10-year period compounded by a similar increase in total hospital charges from \$20,701 in 1997 to \$35,984 in 2006. During this period, no significant improvement in mortality was demonstrated despite considerable advancements in surgical and nonsurgical treatments.³

ANATOMY

The subaxial cervical spine extends from C3 to C7. Each motion segment consists of two subjacent vertebrae

connected by an intervertebral disk, posterior ligaments, and facet joints. Holdsworth et al.⁴ divided the cervical spine motion segments into two columns or elements. The anterior column consists of the anterior longitudinal ligament, anterior annulus, vertebral bodies, transverse processes, posterior annulus, and posterior longitudinal ligament. The posterior column consists of the ligamentum flavum, facet capsules, interspinous ligament, supraspinous ligament, pedicles, laminae, and the spinous processes.⁴ Facet joints are parallel to the frontal plane and 45° to the transverse plane. These contribute to the rotational stability of the subaxial cervical spine. The spinal cord is contained within the spinal canal limited anteriorly by the vertebral body, intervertebral disk, and PLL; posteriorly by the laminae and ligamentum flavum; and laterally by the pedicles and medial aspect of the facet joints. The average magnetic resonance imaging (MRI) anteroposterior and transverse diameters of the spinal cord vary from 8.8 mm × 12.4 mm at C2 to 8.7 mm × 14 mm at C4 and 7.4 mm × 11.4 mm at C7.⁵

DIAGNOSIS

During the initial evaluation, expedient cardiopulmonary resuscitation is of paramount importance while maintaining strict spinal precautions to avoid any iatrogenic neurological injury. Every trauma patient should be assumed

Table 54.1: NEXUS low-risk criteria.

<i>C-Spine radiography is not indicated if all of the following criteria are met</i>		<i>Notes</i>
No posterior midline C-spine tenderness	and	Tenderness extending from the nuchal ridge to T1
No signs of intoxication	and	History; odor of alcohol; ataxia; cerebellar dysfunction; slurred speech
Normal level of alertness	and	Glasgow Coma Score ≤ 14 ; disorientation; altered response to stimuli
No focal neurologic deficit	and	Sensory or motor deficits on neurological examination
No painful distracting injury		Fractures; organ injury; laceration; crush injury; burn

Source: Hoffman JR, Schriger DL, Mower W, et al. Low-risk criteria for cervical-spine radiography in blunt trauma: a prospective study. *Ann Emerg Med.* 1992;21:1454-60.

to have a cervical SCI until proven otherwise. A detailed survey of the face, cranium, and entire spine must be performed to appreciate physical signs of injury including pain upon palpation, ecchymoses, widened interspinous spaces, sagittal deformity, acute kyphosis, or loss of cervical lordosis. A thorough neurovascular examination in all extremities is pivotal to evaluate neurologic compromise during the secondary survey. In a study of 52 patients with a cervical spine fracture found on computed tomography (CT), 40 were identified by history and physical examination alone.⁶ The clinical examination of cervical spine trauma has an overall sensitivity of 76.9%, specificity of 54.7%, positive predictive value of 15.5%, and negative predictive value of 95.7%.⁶ These values decreased in patients who presented with a low Glasgow Coma Score.⁶

In light of this data, prompt radiographic evaluation is critical to diagnose cervical spine injury. Plain film radiography (three-view cervical series) was the standard initial diagnostic test performed for suspected cervical trauma. Two clinical decision rules were developed for expeditious exclusion of cervical injury, selective radiography, and efficient healthcare utilization.⁷ First, the National Emergency X-Radiography Utilization Study Low-Risk Criteria (NLC) published in 1992 (Table 54.1) described five conditions that excluded the need for cervical spine radiography in trauma patients.⁸ This protocol demonstrated a sensitivity of 99.6% and specificity of 12.9% for cervical spine injury.⁹ Second, the Canadian C-spine rule (CCR) (Fig. 54.1) was developed to include high-risk and low-risk criteria and considered neck rotation as part of the evaluation criteria.¹⁰ Stiell et al.⁷ determined that in trauma patients who are alert and stable, the CCR has greater sensitivity and specificity to the NLC, thus resulting in greater radiographic selectivity.

Although plain radiographs were the standard initial diagnostic test performed for suspected cervical trauma, its use has come under considerable scrutiny. Muscle

spasm, edema, and neck pain following blunt trauma may technically limit the acquisition of flexion-extension films.¹¹ In addition, inadequate visualization of vital areas, such as the cervicothoracic junction, has restricted the use of plain films during the initial evaluation of cervical spine trauma. More importantly, the most significant reason for missed cervical spine injury is inadequate radiographic examination.¹²

Helical CT has therefore gained considerable momentum and greater acceptance to evaluate subaxial injury. The advantages of utilizing CT include the elimination of respiratory variations and the visualization of subtle findings that are otherwise masked on plain film.¹³ Also, shorter scanning time allows for prompt diagnosis with real-time interpretation of scans by trauma units.¹³ Helical CT provides image reconstruction, which is essential to visualize cervical alignment.¹³ After the incorporation of this imaging modality into standardized trauma protocols, the detection rate of cervical injury has improved from 54%, with plain film radiography, to nearly 100%.^{13,14}

Both CT and plain film radiography provide poor assessment of soft tissue structures including the intervertebral disk, spinal cord, and surrounding ligaments.¹⁵ In obtunded patients, with negative CT findings whose cervical spine cannot reliably be cleared clinically, MRI may be utilized to effectively assess ligamentous injury.¹⁶ The utilization of MRI to clear the cervical spine is under scrutiny as some authors believe a negative CT suffices for cervical spine clearance.¹⁷ Cervical clearance in the obtunded patient is controversial.¹⁸ Nevertheless, an MRI is indicated in patients with suspected facet subluxation or dislocation and in those with neurologic deficits.¹⁵ Hendey et al.¹⁹ evaluated the incidence of SCI without radiographic abnormality (SCIWORA), which was defined as SCI found on MRI with essentially normal initial plain film radiography in blunt cervical trauma. In SCIWORA patients,

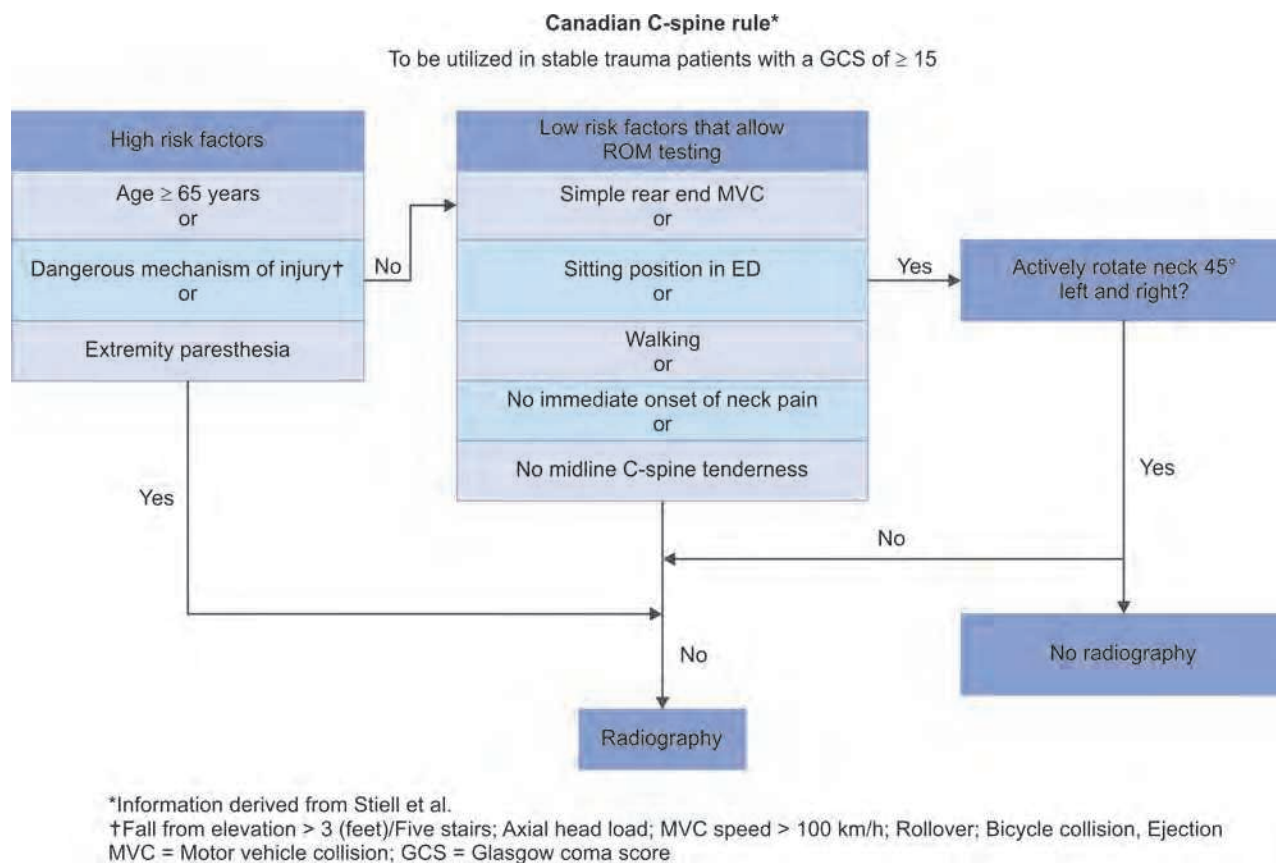


Fig. 54.1: Canadian C-spine rule.

Source: Stiell IG, Wells GA, Vandemheen KL, et al. The Canadian C-spine rule for radiography in alert and stable trauma patients. JAMA. 2001;286:1841-8.

central disc herniation, spinal stenosis, and cord edema or contusions were the most common MRI findings.¹⁹

CLASSIFICATION

Numerous cervical trauma classification methods²⁰⁻²² have been proposed in an attempt to incorporate the mechanism of injury, anatomic deformity, neurologic deficits, and the indications for surgical intervention. The lack of a widely accepted injury classification system has resulted in variability in the management of trauma patients.²³

Allen et al.²⁰ classified subaxial fractures into six categories based on the mechanism of failure. The probability of neurologic deficit was correlated with the type and severity of injury.²⁰ Although commonly utilized, this mechanistic classification scheme has never been validated among spine surgeons.²² Also, the Allen-Ferguson system fails to consider ligamentous stability, neurologic deficits, and is based on plain film radiography.^{22,23}

Subsequently, Anderson et al.²¹ developed the Cervical Spine Injury Severity Score (CSISS) based on both bony and ligamentous injuries.²¹ The CSISS divides the cervical spine into four columns and assigns a scoring system to describe the severity of injury.²¹ Surgical intervention was recommended for patients with a CSISS ≥ 7 .²¹ Although this system has demonstrated reliability, it does not offer insight into the treatment strategies for cervical injuries.²⁴

To address these limitations, Vaccaro et al. developed the Subaxial Injury Classification (SLIC) and Severity Score based on the validated Thoracolumbar Injury Classification and Severity Score system (Table 54.2).^{22,23} This classification scheme incorporates three independent predictors of outcomes: injury morphology, disko-ligamentous complex (DLC), and the neurologic status with subgroups within these categories.²² Each subgroup was provided a scoring system to facilitate decision-making for intervention.^{22,23} If the overall score is ≥ 5 , operative management is recommended. Although this comprehensive

Table 54.2: Subaxial Injury Classification Scale (SLIC).

	Points
Morphology	
No abnormality	0
Compression	1
Burst	2
Distraction	3
Rotation/translation	4
Disco-ligamentous Complex (DLC)	
Intact	0
Indeterminate (interspinous space widening, magnetic resonance imaging changes only)	1
Disrupted (disc space widening, perched facets or dislocation)	2
Neurological status	
Intact	0
Root injury	1
Complete cord injury	2
Incomplete cord injury	3
Continuous cord compression in setting of neurological deficit	+1

Source: Vaccaro AR, Hulbert RJ, Patel AA, et al. The subaxial cervical spine injury classification system: a novel approach to recognize the importance of morphology, neurology, and integrity of the disco-ligamentous complex. *Spine (Phila Pa 1976)*. 2007;32:2365-74.

system determines the need for surgery, it does not evaluate types of surgical intervention for various cervical injuries.²⁵ Therefore, Dvorak et al.²⁵ developed the first surgical treatment algorithm based on a cervical spine injury classification system.²⁵ The algorithm was designed within the framework of the SLIC scoring system and analyzed 26 articles with this classification.²⁵ The authors developed recommendations on the type of surgical intervention for various cervical injuries once the need for operative management was determined.²⁵

Stone et al.²⁶ evaluated the reliability of these three systems by classifying the radiographic images of 50 patients with subaxial cervical spine injuries and documented the need for surgical management.²⁶ The interobserver and intraobserver reliabilities for the CSISS and SLIC scoring systems were “excellent.”²⁶ The Allen-Ferguson system demonstrated “poor” interobserver but “excellent” intraobserver reliabilities.²⁶ With regard to surgical management decisions, the SLIC also demonstrated good interobserver and intraobserver reliabilities.²²

MANAGEMENT OF SELECTED INJURIES

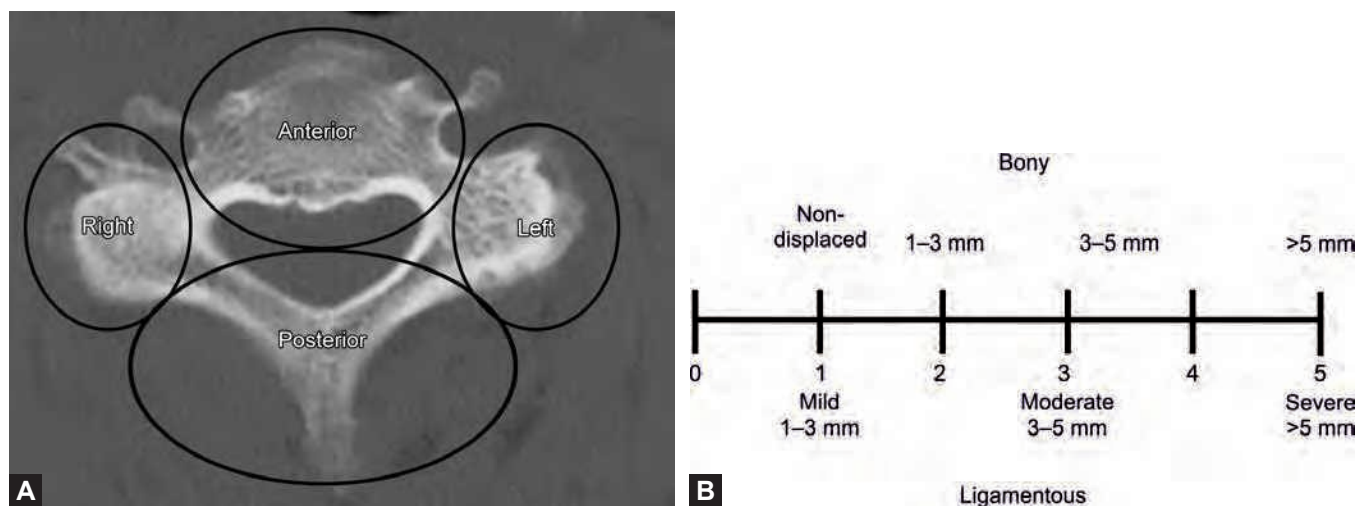
The Spine Trauma Study Group (STSG) recently developed a standardized nomenclature to address the inconsistent terminology of cervical spinal injuries.²⁷ Eleven subaxial injury types and definitions were developed.²⁷ The overall interobserver and intraobserver agreements were 56.4% and 72.8%, respectively.²⁷ Lateral mass fracture, burst fracture, and flexion teardrop fracture were the most agreed upon injury types.²⁷ Therefore, this chapter discusses these selected injury types, and nonoperative and operative interventions based on the SLIC.

Burst Fracture

Vertebral body burst fracture (Figs. 54.2A and B) is associated with a loss of craniocaudal height and involvement of the posterior cortical margin.²⁷ Retropulsion of bone fragments into the spinal canal is often associated with this fracture.²⁷ The SLIC morphology score will be 1 or 2, DLC score of typically 0 (2 if the DLC is involved), and depending on the presence of neurologic injury, an additional 2, 3, or 4 points are added. Therefore, the extent of neurologic involvement underscores the decision for operative management.

Conservative treatment for stable burst fracture includes a halo vest for C3-C6 fractures while a cervico-thoracic brace should be utilized for C7 fractures. Cervical orthoses have demonstrated significant reduction in unrestricted head/base flexion and extension.²⁸ A cervical orthosis achieves transfer of loads through contact with the mandible, occiput, shoulders, and the upper back.²⁹ Appropriate orthosis selection is dependent on patient compliance, complications, and the immobilization capacity of each orthosis.²⁸

Typically, however, operative treatment is preferred for burst fractures. Koivikko et al.³⁰ compared patients with burst fractures treated with skull traction or halo vest with those treated with anterior decompression and stabilization. Surgically managed patients recovered faster with significantly less neurological deficits and kyphotic deformity at final follow-up.³⁰ The results of this study were consistent with other reports that anterior surgical decompression and fusion was superior to conservative management of burst fractures.^{25,30,31} In their algorithmic approach, Dvorak et al.²⁵ also recommended anterior cervical vertebrectomy with cage or strut graft and anterior cervical plating. The benefits of the anterior approach



Figs. 54.2A and B: Sagittal computed tomography of a burst fracture of C5 with retropulsion into the spinal canal.
 Source: <http://radiopaedia.org/cases/cervical-trauma-with-burst-fracture>. Uploaded by Gerry Gardner.



Figs. 54.3A to D: T2-weighted magnetic resonance imaging of flexion teardrop fracture of C5 and traumatic cord edema.
 Source: <http://radiopaedia.org/cases/flexion-tear-drop-fracture-on-mri>. Uploaded by Ahmed Abd Rabou.

include vertebral body resection, direct decompression of the neurologic structures, and stabilization of the injured anatomic structures.^{25,31-34}

Flexion Teardrop Fracture

Flexion teardrop fractures (Figs. 54.3A to D) are associated with a triangular, or quadrangular, bone fragment originating from the anteroinferior vertebral body.²⁷ By definition, concurrent cranial-caudal height loss must be present.²⁷ This injury is in contrast to an extension teardrop fracture found at C2 in the elderly, which is typically stable. Flexion teardrop fractures account for 8–15% of all cervical

fractures.³⁰ The SLIC morphology score will be 4, DLC may be 2, and up to 4 points may be added depending on neurologic manifestation. In general, these injuries require surgical management.

In the literature, one case series reports adequate stability of the cervical spine following only nonoperative management of cervical teardrop fractures.³⁵ The authors describe their closed reduction technique as follows: initial skull traction with halo fixation following 2–6 weeks of skull traction in the supine position.³⁵ Patients were treated with Minerva jackets following 6 weeks of skull traction.³⁵ Of the 10 patients managed with this technique,

only one required surgical fusion due to delayed instability.³⁵ Regardless, the general consensus supports surgical management for this injury due to the high rate of instability and increased risk of neurological injury.³¹ Toh et al.³¹ compared the halo vest and surgical management and established the superiority of decompression and fusion over conservative treatment. Similarly, Fisher et al.³⁶ determined that anterior cervical corpectomy with plating was safe and demonstrated superior outcomes to the halo vest for cervical flexion teardrop fractures.

Dvorak et al.²⁵ recommend a circumferential anterior and posterior open reduction fixation and fusion because the majority of these fractures are associated with significant posterior element failure, thus creating three-column instability. In contrast, Toh et al.³¹ favored an anterior decompression and fusion alone arguing that fixation and postoperative immobilization were enough to avoid a circumferential approach. To compare these techniques, Song and Lee³⁷ analyzed anterior versus circumferential internal fixation and fusion for subaxial cervical flexion injuries, and demonstrated no differences in complications, fusion rate, or neurologic outcomes. Because the majority of teardrop fractures are associated with DLC injury, a circumferential technique may be the best surgical approach for this fracture, especially if a significant posterior injury is found on MRI.²⁵

Facet Subluxation and Dislocation

Unilateral or bilateral facet subluxation and dislocation (Figs. 54.4A to E) result from translational or rotational injury. The deformity is characterized by malalignment of two adjacent vertebrae forming partial apposition of the facet articular surfaces.²⁷ Unilateral facet dislocation occurs when the inferior articular process of the cranial vertebrae has translated anterosuperiorly over the superior articular process of the caudal vertebra.²⁷ Bilateral facet dislocation is the disruption of both facet joints and is associated with comminution or fracture of the facet joint complex.²⁷ Unilateral facet dislocation is associated with <25% translation of the superior vertebral body on that of the inferior vertebral body, whereas bilateral dislocations typically demonstrate >50% translation.³⁸ Perched facets qualify as dislocation so long as no articular surface apposition is appreciated.²⁷

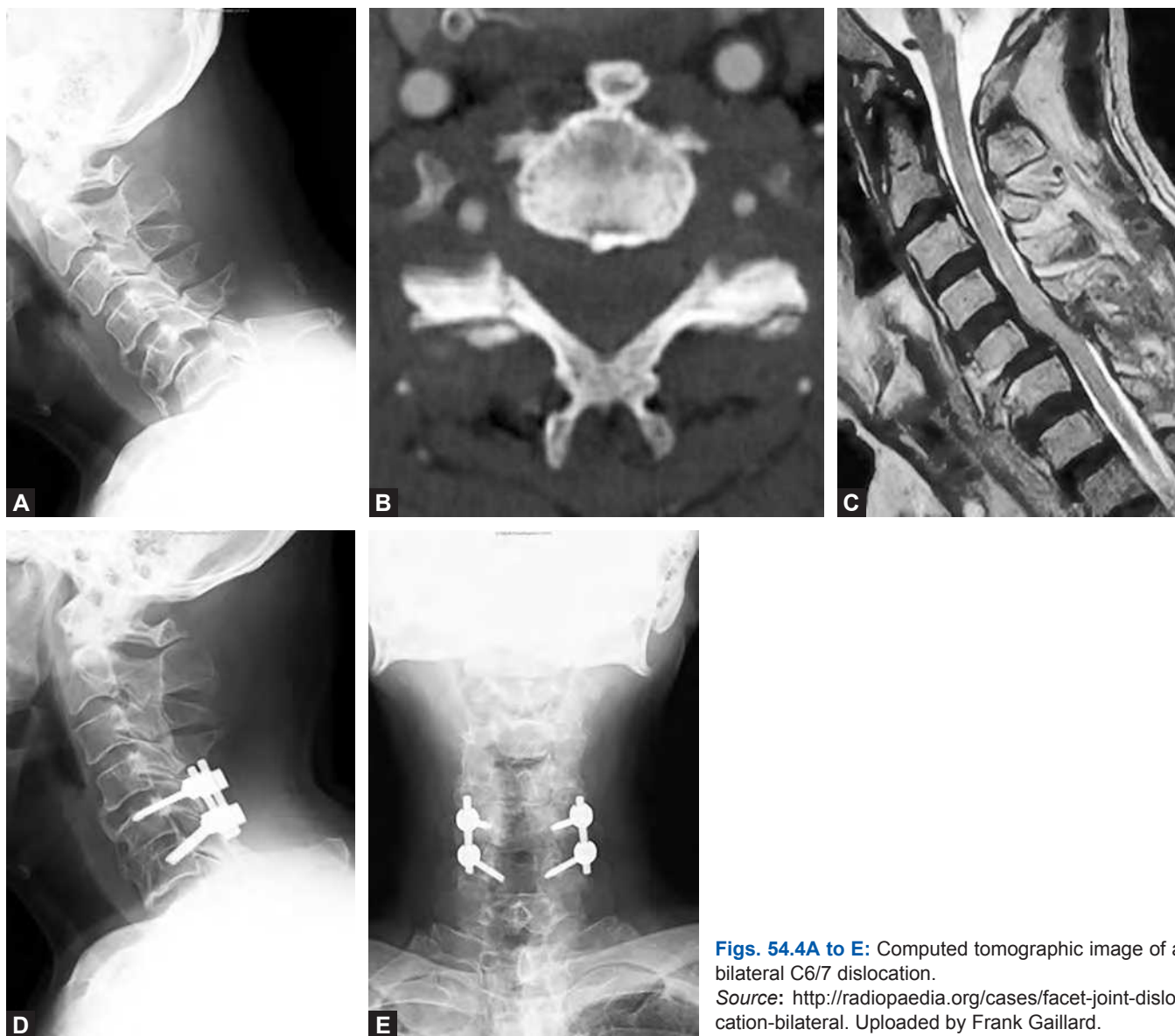
The SLIC morphology score will be 4, the DLC score will be 2, and the neurologic score will vary between 0 and 4 depending on complete and incomplete SCI. Facet dislocations represent the most unstable injuries from subaxial

cervical trauma.^{22,25} In most cases, surgical intervention is necessary to decompress neural structures and to restore stability to the vertebral column.

In these injuries, the intervertebral disc may herniate resulting in spinal stenosis. The timing of MRI is controversial but is typically dependent on the patient's neurologic condition.³⁹ A closed reduction should occur prior to an MRI if the patient presents with a complete SCI.³⁹ In other situations, closed reduction should only be attempted if the patient is awake and cooperative with serial neurologic examinations to monitor neurologic status during the procedure.^{39,40} Otherwise, if obtunded, an MRI should be obtained prior to any intervention.³⁹ Although closed traction reduction prior to an MRI of cervical facet dislocation in awake and alert patients with neural monitoring is acceptable, one case report in the literature by Wimberley et al.⁴⁰ reports acute quadriplegia immediately following this procedure. In such complications, the authors recommend prompt reversal of reduction (i.e. flexion of the cervical spine), SCI steroids, and an emergent MRI to assess neurologic compression.⁴⁰ An emergent surgical neural decompression is warranted if an anatomic compressive pathology is demonstrated on advanced imaging.⁴⁰

Following closed reduction, halo orthosis or continuous traction should be applied to maintain the reduction. Dvorak et al.⁴¹ compared 90 isolated unilateral fractures, subluxations, and dislocations treated surgically versus nonoperatively, and determined that the nonoperative cohort reported greater pain and disability particularly at longer follow-up. This report mirrors similar studies that have demonstrated superior outcomes with surgical intervention.^{34,42,43} In a radiographic series, Beyer et al.⁴⁴ reported that anatomic reduction was achieved in 60% of the operative group compared with 25% of those with an orthosis. In fact, during halo-thoracic immobilization, half of the patients lost reduction.⁴⁴ The burden of cervical instability and risk of neurologic compromise associated with these injuries provide considerable impetus for surgical intervention.

Operative management of traumatic facet subluxation and dislocation is highly variable and is dependent on the patient's neurologic status, presence of disc herniation, and bilateral facet involvement.⁴⁵ Nassr et al.⁴⁵ demonstrated poor agreement among surgeons in regard to interventional treatment options for these injuries. In the presence of a disc herniation, the evidence-based algorithm developed by Dvorak et al.²⁵ recommends anterior cervical discectomy followed by anterior closed reduction of the facet



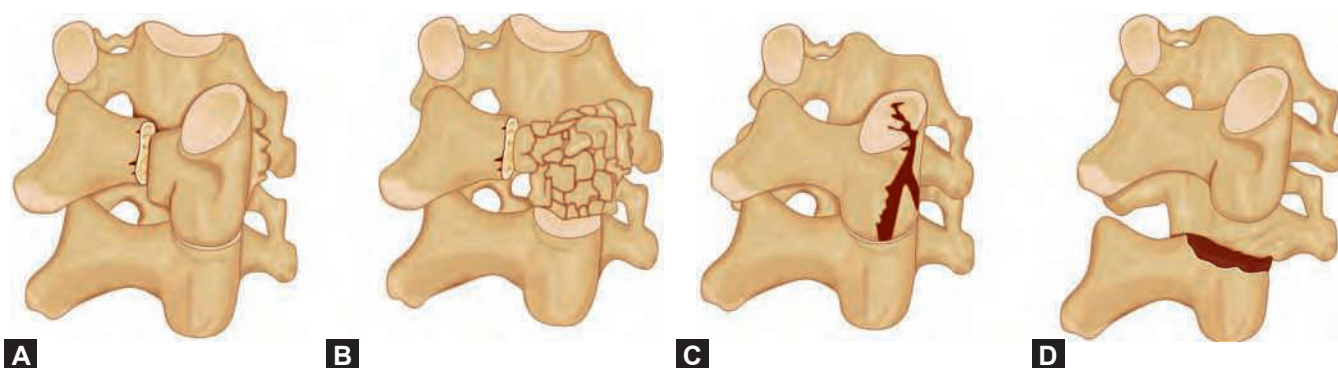
Figs. 54.4A to E: Computed tomographic image of a bilateral C6/7 dislocation.

Source: <http://radiopaedia.org/cases/facet-joint-dislocation-bilateral>. Uploaded by Frank Gaillard.

subluxation/dislocation, and insertion of an interbody graft and plating. The anterior approach is favored to maximize decompression and disc fragment removal.³¹⁻³⁴ If an anterior reduction is unsuccessful, a circumferential open reduction, fixation, and fusion should be attempted.²⁵ The benefits of utilizing a circumferential approach in this situation, once again, include optimal neural decompression with an anterior approach and robust stabilization with posterior instrumentation.²⁵ Without a disc herniation, a posterior approach is utilized to treat ligamentous facet subluxation with the resection of the ligamentum flavum, and a lateral mass fixation and fusion.²⁵ Kwon et al.⁴⁶ demonstrated in a randomized control trial that

both anterior and posterior approaches were valid treatment options though anteriorly treated patients had less postoperative pain, better radiographic alignment, and a lower rate of wound infections.

Bilateral facet subluxations/dislocations are subject to greater degrees of kyphosis following posterior instrumented fusion.⁴⁷ A posterior fusion is utilized to treat bilateral facet injuries in order to provide greater biomechanical stability compared with an anterior approach.²⁵ Progressive disc space subsidence, which resists posterior fixation, is thought to contribute to the postoperative kyphosis.^{25,48} Therefore, some authors recommend early anterior fusion to address this complication.³⁴



Figs. 54.5A to D: Lateral mass fracture classification. (A) type 1; a separation fracture. (B) type 2; a comminution fracture. (C) type 3; a split type. (D) type 4; traumatic spondylolysis.

Lateral Mass Fracture

This fracture is an injury of any portion of the lateral mass complex including the articular process and the pedicle.²⁷ This definition also includes “floating lateral mass” created by ipsilateral fractures of the lamina and pedicle that result in articular process discontinuity with the native vertebrae.²⁷

The mechanism of injury will dictate the SLIC morphology score: one point for compression and four points for rotational or translational injury. The DLC score may be 2 depending on MRI findings. The extent of neurologic compromise can add up to four points. In addition to the SLIC, Kotani et al.⁴⁹ proposed another classification that divided lateral mass fractures into four subtypes: separation, comminution, split, and traumatic spondylolysis. The diagnosis of lateral mass fracture may require advanced imaging such as helical CT. Halliday et al.⁴² reported a 25% detection rate with the use of initial cervical plain film radiography.

In the literature, there is considerable variation regarding the management of these injuries. Nonoperative techniques include the application of a Miami J collar or the halo vest. Lee and Sung⁵⁰ described a case series of 39 patients with lateral mass fractures of which 15 were trialed with a rigid collar. The orthosis was successful in three patients while the remaining required delayed fusion to treat persistent pain and late instability.⁴⁹ Therefore, surgical intervention is likely necessary to provide stability in these injuries. Spector et al.⁵¹ found that unilateral facet fractures with >40% of the absolute height of the intact lateral mass or an absolute height >1 cm are at increased risk for failure of nonoperative treatment.

Kotani et al.⁴⁹ recommend a posterior approach with a cervical pedicle screw fixation for lateral mass fractures

only with minimal disc damage due to the risk of residual anterior translation of the repaired vertebra. Also, severely comminuted fractures with coronal plane malalignment may require two-level posterior fixation (Figs. 54.5A to D).⁴⁹ Single-level anterior arthrodesis of lateral mass fractures may result in failed reduction, cephalad vertebra translation, or malalignment due to short segment fusion.⁵⁰ In these cases, a revision posterior fusion may be required.⁵⁰

SUMMARY

Subaxial cervical spine injuries contribute to the majority of cervical fractures and dislocations. Prompt diagnosis is essential for immobilization and appropriate surgical intervention. Although a number of classifications have been proposed, the SLIC scoring system provides a holistic approach to each injury by characterizing the injury morphology, the disco-ligamentous complex, and the presence of neurological deficits. The subaxial cervical trauma nomenclature designed by the STSG defines 11 types of lower cervical spine injuries, thereby providing a standardized terminology. Although there is considerable variation regarding the management of subaxial injuries, evidence-based algorithms have been proposed to facilitate nonoperative and surgical decision-making.^{25,39}

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Revision Anterior and Posterior Cervical Spine Surgery

Han Jo Kim, K Daniel Riew

Snapshot

» Evaluation

» Causes for Revision Surgery

INTRODUCTION

Revision cervical spine surgery can often be challenging from a technical and clinical perspective. From a technical standpoint, revision surgery requires careful dissection, and preoperative planning secondary to altered anatomy. In addition, revision cervical surgery can be complicated by a lack of bone stock, thereby requiring alternative methods of fixation. Clinically, these cases can be difficult from a diagnostician's perspective because of ambiguity of presentation. For example, a patient with a pseudarthrosis can present with pain that follows a radicular pattern. Such cases require a thorough diagnostic workup, preoperative planning, and execution. When performing revision procedures, the surgeon should do everything possible to ensure that it is the final revision for the operated levels.

EVALUATION

Patients in need of revision cervical spine surgery should all undergo a thorough history and physical examination. Special attention is turned toward changes in the pattern of symptomatology compared to a time point before the index operation, new neurologic deficits, and duration of symptoms. These aspects of the patient presentation can help distinguish complications related to the index operation (i.e. pseudarthrosis and persistent stenosis) versus those that are new (i.e. adjacent segment degeneration).

Radiographic evaluation is an integral part of this diagnostic workup. Standard radiographs of the cervical spine

should include anteroposterior, lateral, flexion, and extension radiographs as well as obliques. These X-rays can help in diagnosing pseudarthrosis, malalignment, and adjacent segment disease as well as evidence of hardware malposition/loosening or failure. If there is evidence of new-onset deformities in the sagittal or coronal planes, and revision surgery requires instrumentation into the upper thoracic spine, long cassette radiographs are helpful in order to assess sagittal balance.

A computed tomography (CT) scan is also performed as an adjunct to plain radiographs. First, it can further delineate the bony anatomy as well as identify subtle pseudarthroses that are not visible on plain radiographs. To diagnose a solid fusion on a CT, there should be bridging bone, not just at the graft-host surface, but also outside the confines of the graft or cage (Fig. 55.1). Second, it also helps to visualize the integrity and position of prior instrumentation. Third, it determines the amount of the bone stock left after the initial surgery. For example, after a patient has had a prior decompression of C2, the CT scan can help in determining the bone stock available for fixation options at that level or if fixation must be extended to levels distal and proximal in order to achieve adequate fixation. Finally, it can help to determine fusion levels. For example, if a patient requires a long fusion down to T2 but happens to have severe facet arthrosis at T2-T3 and an autofusion at T3-T4, only a CT would reveal these findings to the surgeon. Failure to appreciate such a finding would most likely result in poor postoperative outcomes.

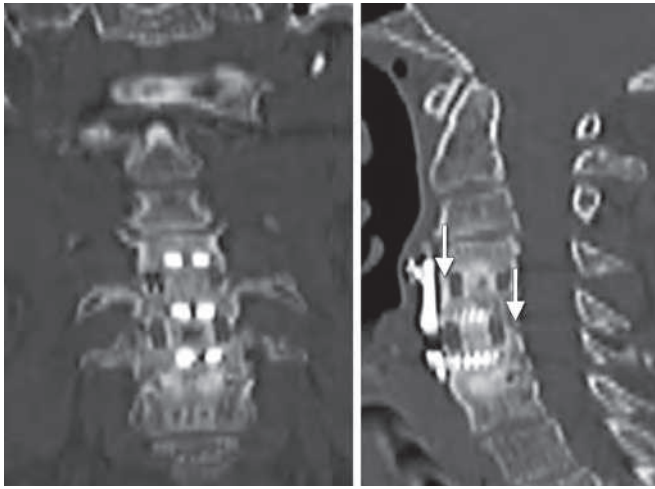


Fig. 55.1: Computed tomography scan demonstrating bridging bone not only within the graft, but also outside (arrows) the confines of the graft.

Magnetic resonance imaging (MRI) is an essential tool in working up a patient with neurologic symptoms after prior cervical spine surgery. MRI is helpful for visualizing the integrity of the neural elements, soft tissues, and in some sequences, fusion status (i.e. T1 sequences). Contrast enhancement can also help in diagnosing recurrent lesions. The only difficulty of MRI in a patient undergoing revision cervical spine surgery is the artifact from previous instrumentation that can make the study difficult to interpret. In such conditions, CT myelography can be helpful.

Electrodiagnostic studies can also be helpful in some cases where the diagnosis might be difficult to obtain with conventional methods. Electromyogram or nerve conduction studies can help distinguish acute versus chronic radiculopathy in patients with residual foraminal stenosis. It may also help in diagnosing pathology unrelated to the cervical spine such as peripheral nerve entrapment syndromes or other conditions such as amyotrophic lateral sclerosis.

Lastly, if the diagnosis is still difficult to make with less invasive methods, a diagnostic nerve root injection can be very helpful in arriving at the correct diagnosis before undertaking a revision surgery. One example is the use of regional injections to the greater occipital nerve in helping to distinguish high cervical radiculopathy versus cervicogenic headaches from prior C1–C2 instrumentation causing irritation of the C2 dorsal root ganglion.

CAUSES FOR REVISION SURGERY

The causes for revision surgery in the cervical spine can be broken down into short-term and long-term etiologies.

Early etiologies include epidural hematomas or wound hematomas, radiculopathy from instrumentation malposition, incomplete decompression, or iatrogenic malalignment (i.e. overvigorous compression of posterior instrumentation to “dial in” cervical lordosis). Late etiologies include pseudarthrosis, late infections, postsurgical malalignment (i.e. cervical kyphosis), and adjacent segment degeneration.

Hematoma

Acute airway compromise from a retropharyngeal hematoma after anterior cervical spine surgery occurs in 0.2–1.9% of cases.^{1–6} Although it occurs uncommonly, the rapid onset and life-threatening possibility of an expanding hematoma can lead to significant patient morbidity and mortality. If a patient is demonstrating difficulty breathing, low pulse oximetry, and clinical signs of asphyxiation, immediate bedside hematoma evacuation by opening the wound is recommended. Patients who are clinically stable, however, can usually undergo controlled hematoma evacuation under general anesthesia. It is important for the surgeon to have a heightened suspicion for high-risk patients such as those who have been on antiplatelet medications, warfarin, or high doses of nonsteroidal anti-inflammatory medications. These patients should be closely watched in the acute postoperative setting.

Sources of bleeding can be active or more commonly from injured, bleeding muscle edges of the longus colli muscles or bony surfaces. It is our routine to inspect the edges of the longus colli before closure and to use bipolar electrocautery to stop any active bleeding as well as Surgicel and Surgiflo to coat the edges of the muscles before closure. In addition, bone wax is used for stopping bone bleeding, especially at the site where the caspar pins were placed. In situations where a corpectomy is performed and there is an abundant area of exposed bleeding bone, we address the bleeding during the surgical procedure with the combination of bone dust (which accumulates from our burr use during a decompression), a patty cottonoid, and some demineralized bone matrix soaked in thrombin. The combination of these and momentary pressure results in dry surgical field. Thus, irrigation to clean out the bone dust is used sparingly since it can aid in achieving hemostasis. In addition, punctate bleeding allows ingress of osteoprogenitor cells, so a completely dry field is not desirable.

For our anterior one-level procedures, this technique for achieving hemostasis has most commonly obviated the use of postoperative drains and has also allowed for one-level anterior cervical decompression and fusions

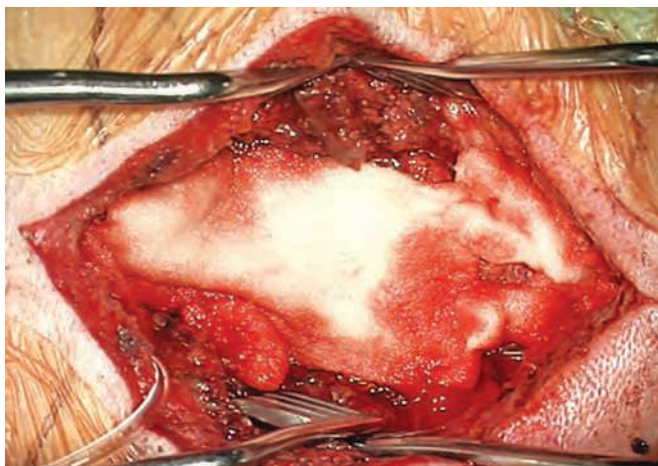


Fig. 55.2: Posterior cervical wound. Before commencing closure, a thrombin-soaked gelfoam is placed within the wound.

(ACDF) to be performed on an ambulatory basis. For multi-level procedures and corpectomies, however, we usually implement a drain overnight to allow for the evacuation of minor oozing. Although we rarely use bone morphogenetic protein 2 (rhBMP-2) in the anterior cervical spine, when we do implement rhBMP-2, we place steroids in the retropharyngeal space. We use Penrose drains for all anterior procedures. Penrose drains are removed the next day, and in the rare event of using a closed suction drain, they are removed when they have <20 cc in an 8-hour shift, typically at 8–16 hours postoperatively.⁷

During our posterior procedures, hemostasis is achieved with a similar combination of bipolar electrocautery, Surgicel and Surgiflo in addition to a gelfoam-soaked thrombin that is cut into a large rectangular shape and placed into the wound before closure (Fig. 55.2). This stops the muscles from bleeding after the closure. One should not place gelfoam or an abundance of hemostatic agents on top of an exposed cord (e.g. after a laminectomy) as these will expand and can result in cord compression. We also place a drain below the hemostatic agent so that a hematoma does not cause cord compression. This method for minimizing blood loss and achieving hemostasis has been successful, and we have seen on average a 100-ml decrease in drain outputs in our posterior cervical cases.⁸ Since we routinely remove the drains once the output is <30 cc/8-hour shift for two consecutive shifts, we have been able to reliably remove drains on the first postoperative day and, overall, decrease the length of stay.

Regardless of the adjunctive product used for achieving hemostasis, meticulous dissection and attention to having a dry surgical field during the approach is an

essential aspect of preventing postoperative hematoma formation in the anterior or posterior cervical spine.

Radiculopathy

Little is reported on the incidence of postoperative radiculopathy. When it occurs, various etiologies from hardware malposition, incomplete decompression with residual stenosis, iatrogenic foraminal stenosis from excessive lordosis, and nerve root irritation are all possibilities to consider. The challenge of managing the patient with persistent pain in the immediate postoperative period lies in the inability to obtain adequate imaging studies at the level that was addressed at the index operation due to metal artifact. Therefore, CT myelogram is the study of choice to examine residual stenosis or remaining osteophytes that can be causing the symptoms. In addition, it can provide sufficient detail of the bony anatomy in order to rule out malposition of the instrumentation. Electrodiagnostic studies can be useful for determining the true etiology of neurologic deficits. This is especially valuable when imaging studies show no evidence of residual stenosis, but the patient has worsened or demonstrated persistent neurologic symptoms. In this situation, the nerve conduction studies can aid in diagnosing alternative explanations for the neurologic findings such as transient ulnar neuropathy or brachial plexopathy from positioning. Nerve conduction studies are useful after the 6- to 12-week time point. Nerve root injections can also be useful as a diagnostic and therapeutic maneuver when postoperative neuroforaminal stenosis is observed.

In posterior procedures, lateral mass screw placement that is too ventral, or a pedicle screw that is not optimally positioned, can result in radiculopathy. In addition, mild foraminal stenosis that is present preoperatively can worsen with excess cervical lordosis built in during surgery. With anterior procedures, foraminal stenosis can occur from an incomplete foraminal decompression or from oversized footprints of some arthroplasty implants that are placed too posteriorly. In either situation, if the cause of the radiculopathy in the acute postoperative period can be localized with a high degree of certainty, revision surgery is recommended in order to rectify the situation if conservative measures such as nerve root injections and pain medication fail.

Adjacent Segment Degeneration

After Hilibrand et al. reported the incidence of adjacent segment pathology (ASP) in the cervical spine to be approximately 2.9% annually and 25% over a 10-year period,

there has been continued controversy on whether ASP is truly a result of altered biomechanics from a fusion or progression of spondylosis in patients who have already demonstrated a propensity toward degenerative disease of the cervical spine.^{1,2,3,9,10} Biomechanical studies have shown altered adjacent disc pressures and motion in response to fusion at adjacent levels, providing objective rationale for the concept of ASP.¹⁰ Clinically, patients with Klippel-Feil syndrome demonstrate areas of degeneration localized most commonly to disc level, directly adjacent to the areas that are congenitally fused.¹² However, large studies on these patients to determine an annual incidence have not been performed, and many patients develop the need for surgery in their 40s, which is much later than what one would expect from degeneration caused primarily by adjacent fused segments.

While the occurrence of ASP may be inevitable, certain techniques can help in minimizing injury to the adjacent level during the index operation. One technique we implement is the use of a hemostat to localize our level. Instead of using a spinal needle to puncture the disk, we use the hemostat to clamp the fibers of the anterior longitudinal ligament or the longus colli muscle corresponding to the level. This prevents the possibility of inadvertently injuring the adjacent disc space. Another technique we use is trying to use the smallest size plate possible (<5 mm within the adjacent levels) in order to prevent adjacent-level ossification development (ALOD).¹³ This is held in position with fixed screws proximally and variable angled screws distally so that when the graft settles, the position of the plate from the adjacent disc level proximally is not shortened. Cranial adjacent levels have shown a higher propensity toward developing ALOD than caudal levels.

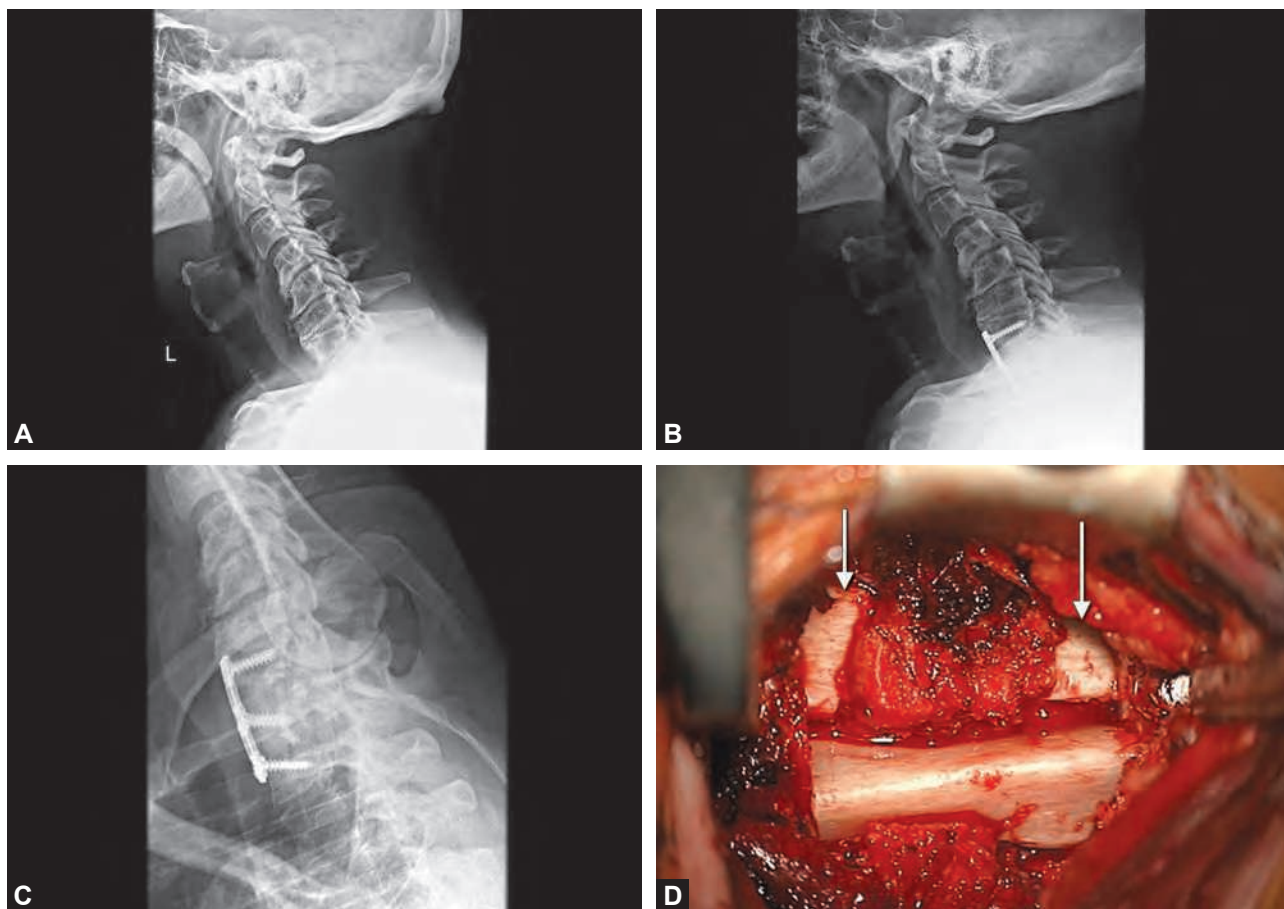
If a revision surgery is needed, the approach is dictated by the difficulty of the anterior versus posterior revision approach. A revision anterior approach is usually not difficult and often is a less morbid procedure for the patient. Usually, before the revision surgery, an otolaryngology consult is performed to ensure bilaterally functioning vocal cords. If there is a unilateral palsy, we perform the approach on the ipsilateral side.¹⁴ If bilateral vocal cords are functioning, an approach can be performed on either side. If for some reason an otolaryngology consult cannot be performed, we perform the surgery on the same side that the prior surgery was performed. If the previous approach was a high cervical one, and the contralateral side is to be approached, then the ears, nose, and throat evaluation needs to assess the integrity of the superior laryngeal

nerve. The superior laryngeal nerve has an internal branch that provides sensation to the posterior larynx. Because it is often dually innervated, damage to one side can be asymptomatic. However, damage bilaterally will result in aspiration from lack of sensation. If the external branch is injured, the loss of constrictor and cricothyroid muscles will result in the inability to scream or sing high notes.

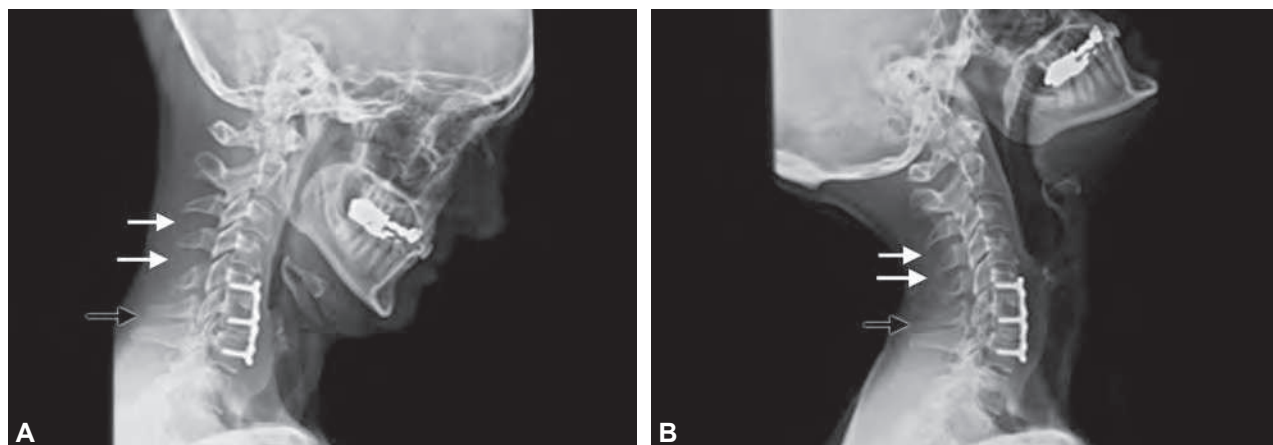
The most common levels seen that develop degenerative disease and undergo ACDF are at the C5–C6 and C6–C7 levels. Therefore, revision surgery for adjacent segment degeneration often involves addressing pathology at C7–T1 or C4–C5. Although the C4–C5 disc space is easily reached with the anterior approach, C7–T1 may be more difficult. For cases like this, we localize our incision to favor the more distal level since it is easier to move proximally than distally. The C7–T1 level can be addressed in the vast majority of cases with an anterior approach as well as the T1–T2 level in some cases. Preoperative imaging can help predict the feasibility of this approach. If a straight line from the skin to the top of the manubrium lies just at or below the posterior aspect of the disc space to be decompressed, then the level can be reached (Figs. 55.3A to D). Sometimes this is only possible by doing a partial corpectomy of the cranial vertebra. Therefore, C8 or T1 radiculopathy does not necessarily portend itself to a posterior approach for addressing the pathology.¹⁵

Pseudarthrosis

Pseudarthrosis can be another reason for revision surgery in the cervical spine. In our experience, pseudarthrosis is the most common reason for recurrence of symptoms after surgery. Usually, it is diagnosed when patients have recurrent symptoms in addition to neck pain with radiographic evidence of failed fusion.^{16,17} This may be evident on plain radiographs by a radiolucent line across the level, loosened implants, and/or graft displacement. In more subtle cases, flexion/extension radiographs can demonstrate motion between the corresponding spinous processes, indicating motion and a likely pseudarthrosis. It is critical that flexion–extension radiographs be adequate. We explain to the patient and the radiology technician that we are looking for maximal flexion and extension views to the limits of the patient's ability. When assessing the adequacy, there must be at least 4 mm of motion at the tips of the spinous processes on one or more unoperated segments (Figs. 55.4A and B). On adequate radiographs,



Figs. 55.3A to D: A patient with T1 radiculopathy. (A) On standing X-rays, a straight line from the manubrium intersects the T1 vertebral body and just skims the posterior superior end plate of T2. This allowed for decompression of the C7–T1 disc space as well as T1–T2 disc space. (B and C) Postoperative X-rays of the surgery. (D) A hemicorporectomy was performed to facilitate decompression for the left-sided symptoms. Also, additional grafts were used in the disc space at the two levels to improve stability and fusion surface area (arrows). Adequate motion in the non-fused segments denote an appropriate flexion/extension image to assess for Pseudarthrosis at the fused segments.



Figs. 55.4A and B: Dynamic flexion–extension radiographs are shown. In order for the dynamic radiographs to be sufficient for diagnosing a pseudarthrosis, at least 4 mm of motion (measured from the spinous processes) should be seen in adjacent unfused levels (white arrows) while the levels that are fused show <1 mm of motion (black arrows) at 150% magnification.

magnified at least 150%, the interspinous process motion should be <1 mm to diagnose a fusion. If for any reason the dynamic views are indeterminate, a CT should be obtained. We have found that the most reliable criterion for a solid fusion is the presence of bone outside the graft within the uncinat process placed by the surgeon. This is especially true in cases where a polyetheretherketone spacer is utilized. Polyetheretherketone often gives the appearance of a solid fusion, especially when it is filled with granular materials. This is why it is imperative to obtain dynamic views and to assess for extra-graft bone formation.

Although rhBMP-2 is rarely used in the anterior spine, we on rare occasions use it for multilevel anterior procedures. Many of the side effects from rhBMP-2 use in the anterior cervical spine seem to be dose related, and we have not seen any of these complications associated with its use at doses we implement, usually 0.2–0.33 mg/level.⁷ Patients are cautioned that the Food and Drug Administration has strongly condemned the use of BMP-2 in the cervical spine as it has caused death, airway compromise due to massive edema, osteolysis, and other complications. New data also suggests the possibility of BMP-2 in high doses being associated with an increased risk of cancers. Other studies have demonstrated increased rates of reoperation and other complications associated with its use. We have not experienced such complications, perhaps due to our low dose and the fact that we place 10–20 mg of Depo-Medrol in the wound before closure, along with 250–500 mg of vancomycin powder. In addition, we put the BMP-2 on demineralized bone matrix instead of the collagen sponge, as it binds well and releases more slowly. With such techniques, our fusion rates for even four- or five-level anterior-only operations have been excellent. The total dose we use in the anterior spine is never more than an XX-Small (1.05 mg). It is imperative to explain the risk-benefit ratio to patients who will be receiving BMP and to have them sign a separate written consent.

The treatment for pseudarthrosis depends on the biomechanics of the construct, location of instrumentation, integrity of remaining bone, patient comorbidities, and patient symptomatology. In considering the biomechanics of the construct, we examine the presence or absence of instrumentation either anteriorly or posteriorly. For example, if a patient had undergone a prior ACDF without instrumentation and developed a pseudarthrosis, we would most likely proceed anteriorly for the revision surgery. This is contrast to pseudarthrosis in a patient who may have undergone a one-level ACDF with instrumentation who

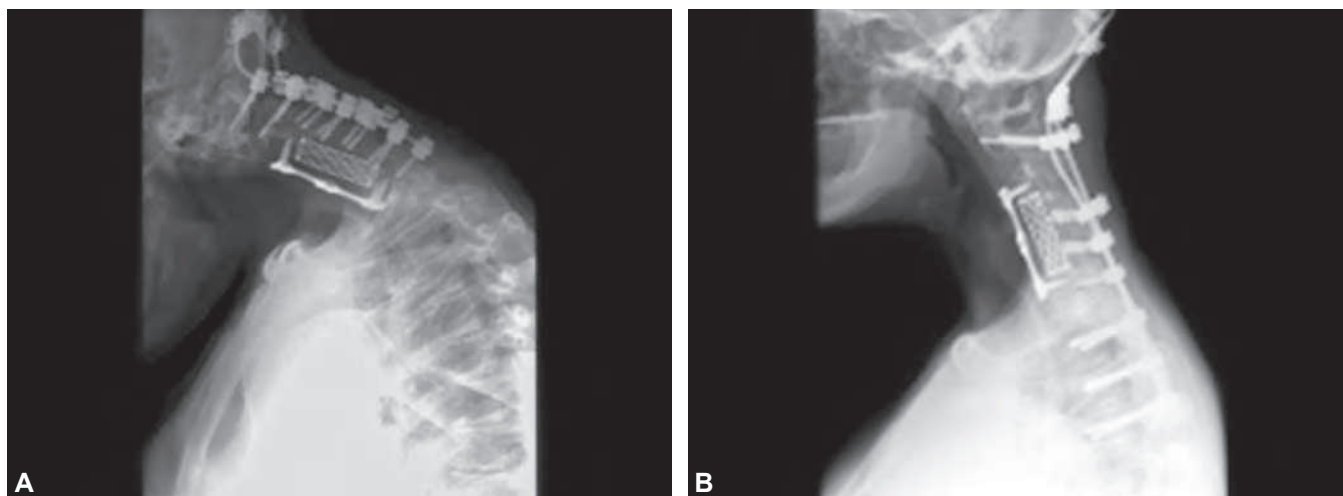
is also a smoker and diabetic. In these patients, we would address the pseudarthrosis with a posterior instrumentation and fusion. In addition, if there was instrumentation that was dislodged or a graft that was displaced, we would be more inclined to pursue an approach in order to address the displaced elements and, depending on the number of levels, perform an anterior or posterior approach as an adjunct. If there is poor remaining bone stock, we would be most inclined to lengthen our construct and/or to perform a combined anterior and posterior approach for addressing pseudarthrosis. Lastly, if a patient presents with radiculopathy localized to the level of the pseudarthrosis, a posterior approach is used in addition to a foraminotomy. This approach will usually lead to a fusion of the anterior cervical spine due to the added rigidity of the posterior instrumentation resulting in a circumferential fusion.

Malalignment

Iatrogenic malalignment can occur due to a variety of reasons and can also manifest as either excessive cervical lordosis or kyphosis. Both patients will present differently. Excessive cervical lordosis can result in iatrogenic foraminal stenosis, necessitating return to the operating room in the acute postoperative period. In this situation, a review of the preoperative films for hypertrophic superior adjacent processes should be utilized since instrumentation artifact will make it difficult to evaluate the foramen. A return to the operative room should involve a posterior foraminotomy in addition to less rigorous compression for generating cervical lordosis.

Malalignment from iatrogenic cervical kyphosis will usually present later with failure at the bone-instrumentation interface at the distal levels of the fusion or in the subacute postoperative period, with patients having difficulty maintaining forward gaze. One additional cause of iatrogenic cervical kyphosis is a kyphosis that develops over time such as that seen in postlaminectomy kyphosis in the uninstrumented spine.

Patients who have difficulty maintaining forward gaze due to their head position usually have had fusions extended to the occiput. This can usually be avoided by having patients take a preoperative radiograph in the position they find most comfortable and then using intraoperative radiographs to match the alignment. This becomes more difficult for cases of chin-on-chest deformities where the deformity does not allow for patients to lift their head to obtain such a radiograph. In this case, limitations on how much extension to aim for during corrective osteotomies



Figs. 55.5A and B: A patient who had an anteroposterior fusion from the occiput to C7 (A), who developed distal junctional kyphosis, was successfully revised to T3 (B) with maintenance of her alignment at 4-year follow-up.

should take into consideration the importance of maintaining some flexion so patients can see their feet during ambulation in addition to ensuring there is mild laxity to the anterior soft tissue structures such as the strap muscles as well as the esophagus in order to allow for swallowing. Excessive tension by overcorrection can result in an inability to swallow, which will necessitate revision surgery or the use of a percutaneous endogastric feeding tube until the esophagus can be retrained in its new position.

Distal junction kyphosis can be seen in cases where the proximal lever arm created by the fusion mass lies too anterior to the trunk, resulting in excessive stress at the bone-screw interface at the distal levels (Fig. 55.5A). Anecdotally, we have had less distal problems when the construct is made in a way that a plumbline from the basion is anterior to the manubrium after the corrective osteotomies are performed (Fig. 55.5B).

Postlaminectomy kyphosis occurs in up to 30–40% of cases for patients with neutral alignment.^{18,19} Careful posterior dissection being mindful of the laminectomy defect is the most tedious portion of the approach. Once the lateral masses are exposed, instrumentation is implanted. For cases where there is excessive scar posteriorly over the thecal sac, care must be taken not to cause buckling of the scar when generating a physiologic amount of cervical lordosis. Excessive scar tissue can be excised with a No. 15 blade once the interval between the dura and scar is identified bluntly with a cervical Cobb elevator (Fig. 55.6). It is also important to examine the preoperative MRI and/

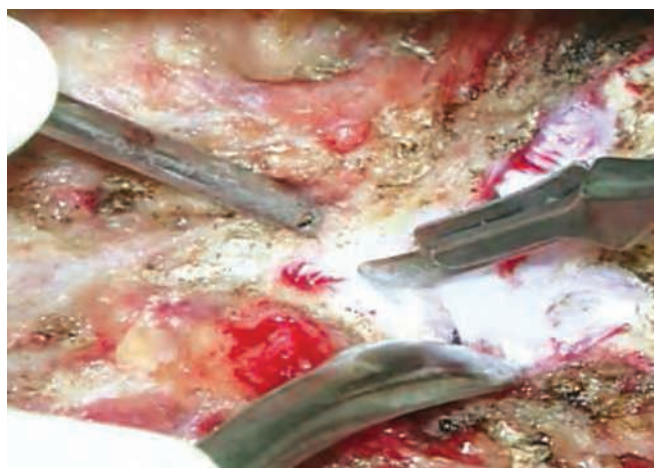


Fig. 55.6: Sharp and blunt dissection is used to “peel” the scar off the dura. As mentioned in the text, the Cobb is held in a way that half of it lies on the bony facet and determines the depth of our sharp dissection. Once a plane is delineated, the majority of the scar can be peeled off slowly.

or CT to determine how dorsal the dural sac protrudes past the bony lamina of the segments above and below the laminectomy defect. The spinous processes are exposed subperiosteally and then continued to the laminar defect, stopping when the dissection is 5–10 mm above the dura (based on preoperative imaging studies). After exposing the cord, care is taken to avoid dropping anything on top of it, especially while instrumenting.

Regardless of the type of malalignment, revision surgery should involve an evaluation of the flexibility of the defor-

mity. Rigid deformities will necessitate osteotomies, while flexible deformities do not.²⁰ Usually, plain radiographs in the upright and supine positions can be an indication of the flexibility of a deformity. For revision surgery where prior instrumentation was performed, a CT scan can help in identifying fused and nonfused segments for adequate preoperative planning. It has been our experience that an anteroposterior combined approach, when possible, results in less blood loss and less operative time while providing similar corrections to a pedicle subtraction osteotomy. The caveat to this is that in severe deformities, an anterior approach is not feasible and in such cases, a pedicle subtraction osteotomy is the only option. Otherwise, an anterior osteotomy combined with posterior column osteotomies (Smith-Petersen or Ponte type) should be able to provide adequate correction in most cases.

KEY POINTS

- Early etiologies for revision surgery include epidural hematomas or wound hematomas, radiculopathy from instrumentation malposition, incomplete decompression, or iatrogenic malalignment. Late etiologies include pseudarthrosis, late infections, postsurgical malalignment (i.e. cervical kyphosis), and adjacent segment degeneration.
- In our experience, pseudarthrosis is the most common cause for revision surgery. It can be approached via an anterior or posterior approach based on the biomechanics of the construct, location of instrumentation, integrity of remaining bone, patient comorbidities, and patient symptomatology.
- The ALOD after ACDF can be minimized by keeping the plate at least 5 mm from the adjacent cranial disc space.
- In addressing cervical deformity cases, it is our recommendation to bring the basion plumbline as close as possible to the manubrium to prevent distal junction kyphosis.
- In performing corrective osteotomies for sagittal plane deformities, some flexion should be maintained so patients can see their feet during ambulation in addition to ensuring there is mild laxity to the anterior soft tissue structures, such as the strap muscles and esophagus, in order to allow for swallowing.

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Landmark paper that determined the rates of adjacent segment disease based on over 370 patients. The authors determined that the annual risk of adjacent segment degeneration was approximately 2.9% and 25.6% at 10 years. C5-6 and C6-7 were the level at highest risk.

Buchowski JM, Riew KD, Nussenbaum B. In reference to acute airway obstruction in cervical spinal procedures with bone morphogenetic proteins. *Laryngoscope.* 2011;121(11):2501; author reply 2502-3.

A letter to the editor in regards to airway obstruction in cervical spine procedures associated with BMP use. No acute airway obstructions due to BMP use were noted by the authors at their dosage use of approximately 0.4–0.6 mg/level.

SECTION

6

Spinal Cord Injury

Kazuhiro Chiba

Acute Management of Spinal Cord Injury

Shelly Wang, Jefferson R Wilson, Michael G Fehlings

Snapshot

- » Epidemiology and Costs
- » Prognosis
- » Pathophysiology
- » Initial Assessment
- » Radiographic Assessment
- » General Medical Care
- » Surgical Management of SCI
- » Traction/Reduction of Cervical Spine Injuries
- » Pharmacologic Management
- » Emerging Therapies

INTRODUCTION

Acute traumatic spinal cord injury (SCI) is a devastating condition oftentimes accompanied by a cascade of complications including hemodynamic instability, pulmonary dysfunction and metabolic derangements. The acute management of SCI is multifaceted and is crucial to long-term neurologic prognosis. Initial assessment should focus on early stabilization of the cervical and thoracolumbar spines to prevent repeated injury, followed by transportation to an appropriate acute care setting for diagnosis and treatment. Respiratory and hemodynamic status should be rapidly assessed and corrected to mitigate ongoing injury to the spinal cord ischemic penumbra. Spinal instability and ongoing compression should be addressed through early closed reduction or surgical decompression, and the judicious use of corticosteroids can be considered for neuroprotection in patients presenting within 8 hours of injury.

In addition to established guidelines, this chapter will also touch on novel treatments on the cusp of human translation. Minocycline, riluzole, and Cethrin® target various aspects of the secondary injury cascade and hold promise as neuroprotection agents. Stem cell transplantation allows for replacement of lost cells in addition to protection of surviving axons, and has shown promise

in models of both acute and chronic SCI. Lastly, therapies including cerebrospinal fluid (CSF) drainage and therapeutic hypothermia have also been shown to be beneficial in animal models and to be safe in human phase I/II trials, and thus constitute an exciting area of investigation with potential for incorporation into future treatment algorithms.

EPIDEMIOLOGY AND COSTS

The worldwide annual incidence of acute traumatic SCI is 15–40 cases per million, which carries significant socioeconomic impact.^{1,2} In the United States, the prevalence of SCI is 270,000 with 12,000 new cases occurring annually.^{3–5} Common mechanisms of injury include motor vehicle collisions (39.2%), falls (28.3%), violence (14.6%), and sporting accidents (8.2%).⁴ The majority of acute SCI patients are males (80.6%), and the average age of injury is 40.6 years, with a peak in young adulthood due to violence and accidents, and a second smaller peak in the elderly due to increased falls.⁴

Approximately 60–75% of acute SCI occurs in the cervical spine, 15% in the thoracic spine and 10% in the lumbosacral spine.^{1,6} Despite advancements in the acute management and supportive care of SCI, 15–20% of patients die prior to arriving in hospital.⁷ In the surviving

population, prognosis is particularly poor in high tetraplegia and ventilator-dependent patients, who face a 1-year mortality of 8.2% and a life expectancy of only 10–15 years post injury—septicemia and pneumonia are the leading causes of death in these patients.^{3,4,8} The societal and individual costs of SCI are extensive. Depending on the level and severity of injury, expenditure associated with acute care, rehabilitation, and lost productivity can exceed \$1 million in the first year after injury and up to \$25 million in a lifetime.^{4,8}

PROGNOSIS

The all-cases cumulative survival of acute SCI is 94% at 1 year and 86% at 10 years.⁹ Mortality is predicted by multiple factors, including increasing age, higher level of neurologic injury, and concomitant traumatic brain injury (TBI) or severe systemic injury.^{10,11} Complete SCI patients experience mortality rates that are three times higher compared to their incomplete SCI counterparts.⁹ In an Australian study, at 10 years post injury, 22% of C1–C4 SCI patients had died compared to 13% of C5–C8 patients and 7% of T1–S5 patients.⁹ Geriatric SCI patients > 70 years of age suffered higher in-hospital mortality of 27.7% compared to 3.2% for adults younger than 70.¹²

The neurologic prognosis following SCI is dependent on the level of injury and American Spinal Injury Association Impairment Scale (AIS) grade on presentation, with the extent of anticipated recovery diminishing as the injury severity increases.¹¹ On average, at 1-year follow-up, AIS A patients will improve 12 points in the ASIA Motor Score (AMS) compared to 28 points for AIS B patients, and 43 points for AIS C patients. At 1 year, approximately 10–15% of AIS A patients will convert to incomplete status, with only 2% improving to AIS D. One-third of AIS B patients will improve to AIS C, and one fourth to AIS D or E. Seventy percent of AIS C patients will improve to AIS D or E. The motor gains are more limited in AIS D patients, with only 4% converting to AIS E, largely due to the ceiling effect. There is a consensus across literature that patients with complete thoracic SCI have a reduced potential for neurologic recovery compared to their cervical SCI counterparts due to (1) increased force required for thoracic spine disruption, likely resulting in increased neural tissue damage, and (2) inability to detect neurologic change in T2–T12 levels, thus neglecting any neurologic improvement that may occur. This difference was not observed in incomplete SCI.

PATHOPHYSIOLOGY

Acute SCI consists of the initial traumatic event known as the primary injury, followed by a prolonged and progressive cascade of events constituting the secondary injury. At a macroscopic level, primary injury results from a compressive force applied to the spinal cord arising from (1) bone, disc or ligamentous material extruding into the spinal canal, (2) extradural hematoma formation, or (3) dynamic instability of the spinal column.^{13,14} Diffuse axonal injury, petechial hemorrhages, and vascular shearing can also result from distractive forces. Within seconds, the initial spinal cord trauma initiates a signaling cascade of downstream events collectively known as the secondary injury. The neuroinflammation, free radical formation, glutamine-mediated excitotoxicity, and lipid peroxidation lead to gradual expansion of the initial lesion in a rostrocaudal direction from the injury epicenter.⁸ As a result, gray matter loss and white matter degeneration persist for up to several weeks, contributing to neurologic decline in a prolonged and progressive fashion. In addition, reactive astrocytes interact with microglia, undergo morphological changes, and increase synthesis of glial fibrillary acidic protein.¹⁵ This process is the main component of astrogliosis, leading to the formation of a hostile environment not conducive to neural regeneration. While injury prevention and early closed or open reduction aim to mitigate primary injury, the majority of neuroprotective agents target stages of the secondary injury cascade to attenuate the neuroinflammatory responses.

INITIAL ASSESSMENT

Assessment and management of acute SCI begins at the scene. Approximately 20% of cervical SCI involve multiple noncontinuous vertebral levels, and 35% are associated with TBI.¹⁶ Therefore, assessment of multisystematic trauma, level of consciousness, spinal pain or tenderness, and focal neurologic deficits is important in the context of SCI. Patients at risk for spinal injury should be immobilized with a combination of rigid cervical collar and supportive blocks on a backboard, in addition to log-roll techniques to secure the entire spine.¹⁷ Following initial assessment and resuscitation, the patient should be transported to the nearest capable definitive medical care facility, and to a SCI treatment facility if possible.¹⁸

In alert and cooperative patients, assessment of neurologic deficits, spinal step deformities, and local tenderness provides insight into the diagnosis of SCI. Neurologic

Table 56.1: ASIA impairment severity (AIS as modified from Frankel) grade classification.¹⁹

Class	Description
A	<i>Complete:</i> no sensory or motor function is preserved in sacral segments S4 and S5
B	<i>Incomplete:</i> sensory, but not motor, function is preserved below the neurologic level and extends through sacral segments S4 and S5
C	<i>Incomplete:</i> motor and sensory function is preserved below the neurologic level. Most key muscles below the neurologic level have a muscle grade of <3
D	<i>Incomplete:</i> motor and sensory function is preserved below the neurologic level. Most key muscles below the neurologic level have a muscle grade of ≥3
E	<i>Normal:</i> sensory and motor functions are normal

assessment should proceed in accordance with the ASIA International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI).¹⁹ Originally developed in 1982, the ISNCSCI consists of three main components and is the most widely accepted classification system in clinical use.²⁰ The AMS is based on the power of 10 myotomes bilaterally, rated between 0 (no movement) and 5 (full power). The ASIA Sensory Score consists of pinprick and light touch sensation based on 28 dermatomes bilaterally, ranging from 0 (no sensation) to 2 (normal sensation). Lastly, the neurological level of injury identifies the spinal level of at least three-fifths power and sensory function bilaterally. Outlined in Table 56.1, the AIS classification sorts SCI into five categories from AIS A (complete injury, no motor or sensory function) to AIS E (normal examination). In addition to the initial assessment, SCI patients should be examined serially throughout hospitalization, specifically at 72 hours post injury for an accurate baseline examination following resolution of potential confounding spinal shock, and at 1 month post injury for prognostication of neurologic recovery.²¹

RADIOGRAPHIC ASSESSMENT

Radiographic diagnosis of cervical SCI begins with two assessment tools, developed through multicenter prospective observational studies, to stratify risk for cervical spinal injury. The National Emergency X-Radiography Utilization Study (NEXUS) assessed five factors in the prediction of cervical spine injury and concluded that patients who have no neurologic deficits, normal alertness, no intoxication, no midline cervical tenderness, and no painful distracting injury have a 99.8% negative predictive value for

cervical spine injury.²² The Canadian C-Spine Rule (CCR) provides an alternative assessment algorithm based on patient age, injury mechanism, extremity paresthesia, and cervical range of motion.²³ Retrospective analyses comparing the validity of these two scores found the CCR to be more sensitive and specific than the NEXUS low-risk criteria (NLR) for detection of cervical spine injury,^{24,25} although both scores are widely used in the Emergency Department. Low-risk patients determined by the CCR or NLR should be cleared of cervical immobilization without radiographic evaluation.¹⁸

In alert and symptomatic patients with spinal tenderness, neck pain, or neurologic deficits, further investigation with computed tomography (CT) or high-quality three-view cervical spine radiographs (CSR) should be used for injury assessment. Computed tomography is the imaging modality of choice, as it is very sensitive for defining bony fractures, spinal deformities, and canal patency. In the literature, CT has demonstrated superiority in cervical spine fracture detection, approaching 100% sensitivity compared to 36–64% sensitivity with CSR.²⁶ When CTs are not available, high-quality three-view CSR covering the entire spine from the craniocervical junction to the C7–T1 junction can be used. Abnormal spinal alignment or angulation, widening of joint and disc spaces, and presence of soft tissue swelling all contribute to possible diagnosis of spinal injury.

Patients with CT or X-ray evidence of spinal injury should undergo magnetic resonance imaging (MRI) to (1) identify pattern and anatomic level of cord injury for prognostication, and (2) identify soft tissue injury, ligamentous disruption, intervertebral disc herniation, or vertebral artery injury that will affect overall management. MRI is also valuable and recommended for elderly patients with comorbid spinal conditions like ankylosis, ankylosing spondylitis and diffuse idiopathic skeletal hyperostosis (DISH). T2 sagittal views are the most helpful for the detection of cord injury.²⁷ In one prospective study, the presence of hemorrhage, edema, cord swelling, increased spinal cord compression and canal compromise, as well as longer rostrocaudal lesion length, was associated with worse clinical prognosis.²⁸ MRI or dynamic flexion–extension cervical spine X-rays can also be provided as options for symptomatic patients with a normal CT, although their roles in the management of those patients are less evident.²⁶

All obtunded patients should undergo high-quality CT as the first imaging modality of choice, since no reliable clinical examination is available. In the case of a normal

CT, multiple prospective studies and retrospective reviews have attempted to appraise the role and value of MRIs in detecting what CTs have missed. Proponents advocate for its use in evaluating ligamentous injury; in one large meta-analysis, MRI detected abnormality in 12% of CT-negative patients, leading to altered management (surgical stabilization or immobilization) in 6%.²⁹ These meta-analyses are balanced with other data that reveal no added benefit in obtaining MRI. To reconcile conflicting class II/III evidence, the 2013 American Association of Neurological Surgeons (AANS) and Congress of Neurological Surgeons (CNS) guidelines advocate the following strategies for obtunded patients with normal CT: (1) continue cervical immobilization until asymptomatic, (2) discontinue cervical immobilization following a normal MRI study obtained within 48 hours of injury, or (3) discontinue immobilization at the discretion of the treating physician.²⁶ Routine use of dynamic flexion–extension X-rays is of marginal benefit and is not recommended.²⁶

GENERAL MEDICAL CARE

Progressive secondary injury follows the initial insult and is aggravated by local hypoxia and systemic hypotension. Demonstrated in animal and human studies, early identification and management of systemic hypoxia, pulmonary dysfunction, and cardiovascular instability plays a large role in mitigating secondary injury and improving neurologic outcome.

As per Advanced Trauma Life Support protocol, the primary survey of trauma patients includes assessment of airway, breathing, and circulation. Respiratory distress, tachypnea, desaturation, or a decrease in forced vital capacity below 15 mL/kg should be addressed.³⁰ Adequate oxygenation and mechanical ventilation is especially crucial for patients with high SCI above C5 due to loss of both intercostal and diaphragmatic innervation. In addition, patients with injuries above T6 are at risk of neurogenic shock from interruption of sympathetic pathways, leading to unopposed vagal stimulation and decreased systemic vascular resistance. These patients often demonstrate hypotension refractory to fluid resuscitation, relative bradycardia, and hyperemic warm skin. Approximately 25% of cervical SCI patients experience hypotension (systolic blood pressure <90 mm Hg) with relative bradycardia (heart rate < 90 bpm) acutely after injury, and patients with complete SCI are 5.5 times more likely to develop refractory hypotension compared to those with incomplete SCI.³¹

To support spinal cord perfusion pressure and to avoid ischemia, a mean arterial pressure (MAP) between 85 and 90 mm Hg should be maintained for the first 7 days following injury.³² Concomitant sources of hemorrhage and hypovolemia should be corrected, and judicious use of isotonic crystalloid fluids is the first-line therapy for hypotension. For neurogenic shock unresponsive to fluids, vasopressor agents should be considered to prevent iatrogenic pulmonary edema, congestive heart failure, and hyponatremia secondary to fluid overload. To address both peripheral vasodilation and bradycardia, an agent with both α - and β -adrenergic activity such as dopamine or norepinephrine is desirable.³³ Phenylephrine should be avoided due to its exclusive α -receptor activity and propensity to exacerbate reflexive bradycardia through peripheral vasoconstriction. Atropine, or in refractory cases, pacemaker placement, can be used to correct bradycardia.

For patients with SCI above T6, temperature regulation also presents as a challenge due to lack of effective afferent pathways from skin receptors and the inability to regulate vasoconstriction, vasodilation, and sweating in the insensate portion of the body.³⁴ Partial poikilothermia develops, leading to drastic shifts in core body temperature in concordance with ambient temperature.³² Metabolic derangements, including post-traumatic hypokalemia, may occur in up to 54% of SCI patients, hypothesized to be a result of increased plasma epinephrine release during periods of hypovolemia and hypotension.³⁵ Pulmonary dysfunction, gastrointestinal ileus, urinary retention, deep vein thrombosis, autonomic dysreflexia, and decubitus ulcers are also common in SCI patients and should be prevented or treated early in the disease course.

Even in situations of initial hemodynamic stability, patients with acute cervical SCI are at risk for life-threatening episodes of hypotension, bradycardia and cardiac irregularities, especially over the first week.³⁶ Based on level III evidence, the AANS/CNS guidelines recommend admission into an intensive care unit for the first 7–14 days, during which patients are particularly susceptible to complications.³² In the United States since 2005, the median length of stay in an intensive setting following SCI was 11 days, but increased for patients with neurologically complete injuries.³⁷ Adequate early medical care in an appropriate setting is crucial in the management of SCI. Some important guidelines and the accompanying level of evidence are presented in Table 56.2.

Table 56.2: Guidelines for the acute management of spinal cord injury.

Parameter	Guidelines	Level of evidence
Early immobilization	Spinal immobilization for all trauma patients with a combination of rigid cervical collar, supportive blocks on a backboard with straps and log-roll technique	III
Hemodynamics	Correction of hypotension (sBP < 90 mm Hg)	III
	Maintenance of MAP between 85 and 90 mm Hg for the first 7 days following acute SCI	III
Care setting and monitoring	Management of patients with acute cervical SCI in an intensive care unit or similar monitored setting	III
	Use of cardiac, hemodynamic, and respiratory monitoring devices to detect cardiovascular dysfunction and respiratory insufficiency	III
Thromboembolism prophylaxis	Venous thromboembolism prophylaxis including the use of low molecular weight heparin, pneumatic compression boots and rotating beds	II

Table 56.3: The subaxial cervical spine injury classification system.⁴⁴

Parameter	Points
Morphology	<ul style="list-style-type: none"> No abnormality 0 Compression 1 Burst +1 = 2 Distraction (i.e. facet perch, hyperextension) 3 Rotation/translation (i.e. facet dislocation, unstable teardrop or advanced staged flexion compression injury) 4
Integrity of discoligamentous complex (DLC)	<ul style="list-style-type: none"> Intact 0 Indeterminate (i.e. isolated interspinous widening, MRI signal change only) 1 Disrupted (i.e. widening of disc space, facet perch or dislocation) 2
Neurologic status	<ul style="list-style-type: none"> Intact 0 Root injury 1 Complete cord injury 2 Incomplete cord injury 3 Continuous cord compression in setting of neuro deficit +1

SURGICAL MANAGEMENT OF SCI

A select group of SCI patients would benefit from surgical decompression, with goals to (1) restore biomechanical stability to the spinal column and (2) optimize neurological outcomes by decompressing the spinal cord and neural elements.³⁸ A combination of factors should be taken into consideration when making the decision to operate, including the presence of neurologic deficit, mechanism of injury, biomechanical stability, osteoligamentous integrity, and fracture morphology.³⁸ Multiple classification systems have been developed on the basis of injury mechanism and radiographic features to serve as tools for clinical decision making. These include the Allen-Ferguson Classification³⁹ and the Harris Classification⁴⁰ for cervical

spine injuries, and the three-column Denis Classification⁴¹ and AO/Magerl Classification⁴² for thoracolumbar spine injuries.

In 2005 and 2007 respectively, the Spine Trauma Study Group developed the thoracolumbar injury classification and severity score (TLICS)⁴³ and the subaxial injury classification (SLIC).⁴⁴ These scores were designed to provide a surgical candidacy appraisal based on the natural history and biomechanics of these spine injuries, and have since gained widespread acceptance in clinical practice. The three components of the scoring system include (1) injury and fracture morphology, (2) integrity of the discoligamentous complex or posterior ligamentous complex (PLC), and (3) neurological status (Tables 56.3 and 56.4). The subgroups under each category were assigned a score,

Table 56.4: The thoracolumbar injury classification and severity score.⁴³

Parameter		Points
Morphology	• No abnormality	0
	• Compression	1
	• Burst	+1 = 2
	• Translation rotation	3
	• Distraction	4
Integrity of posterior ligamentous complex	• Intact	0
	• Suspected/indeterminate	2
	• Injured	3
Neurologic status	• Intact	0
	• Nerve root	2
	• Conus medullaris (complete)	2
	• Conus medullaris (incomplete)	3
	• Cauda equina	3

with a higher score reflecting a greater perceived need for operative intervention. For both the SLIC and TLICS systems, a total score of ≥ 5 suggests benefit from surgical intervention, whereas ≤ 3 suggests benefit from conservative management. A score of 4 suggests that the injury may be managed at the discretion of the surgeon involved. The SLIC score is the classification system recommended by the AANS/CNS for its excellent inter-rater reliability and ability to communicate both clinical and radiographic information in addition to radiographic information.⁴⁵ Similarly, the TLICS score was found to have good inter-rater and intra-rater reliability among spine surgeons in a recent multicenter reliability study,⁴⁶ and is widely used around the world.

For surgical candidates, there is emerging evidence and consensus among spine surgeons in favor of early decompression within 24 hours of SCI. For many years, the timing of surgery was controversial as the benefits from early alleviation of ongoing cord trauma was balanced by concerns regarding intraoperative exacerbation of hemodynamic instability.⁴⁷ However, animal data over the decades have demonstrated a temporal relationship of spinal cord compression in behavioral recovery, spinal cord blood flow disturbances, electrophysiological recovery, and histopathological lesion.⁴⁸ Human data consisting of nonrandomized prospective controlled trials and retrospective reviews supported the safety of early surgical decompression but yielded conflicting data regarding its efficacy. The first randomized controlled trial (RCT) of

early surgical decompression in cervical SCI attempted to discern the role of early (< 72 hours) versus late (> 5 days) decompression.⁴⁹ Unfortunately, 20 of the 62 patients originally enrolled were lost to follow-up and no neurologic difference was attributed to timing of decompression.

Recently published in 2012, two prospective cohort studies were completed to discern the role of early (< 24 hours) surgical decompression. The Surgical Timing in Acute Spinal Cord Injury Study (STASCIS) is the largest multicenter prospective cohort study on the timing of surgical decompression in SCI to date, involving 313 adults with acute cervical SCI who received early versus late surgical decompression.⁵⁰ At 6 months, early surgical decompression was associated with a statistically significant 2.8 time increase in patients exhibiting at least a two-grade improvement in AIS, with no difference in acute complication rates between the two groups. A second study involved 84 SCI patients in the Ontario Spinal Cord Injury Registry program who received early versus late surgical decompression.⁵¹ Of the 55 patients with neurological examination available at rehabilitation discharge, there was also a statistically significant increase in the number of patients showing at least a two-grade AIS improvement in the early surgery group. In addition to clinical evidence supporting early surgical decompression, it is considered by many clinicians as feasible and the standard of care for incomplete SCI. In a 2010 case-based survey of 971 international orthopedic and neurosurgery spine surgeons, approximately 80% preferred to decompress an unstable, incomplete SCI (ASIA B-D) within 24 hours of injury, except in the case of central cord syndrome due to its propensity for spontaneous neurologic improvement over the ensuing weeks.⁵² A subgroup of surgeons recognized the role of ultra-early surgical decompression; specifically, 72.9% would operate within 6 hours for incomplete SCI and 46.2% would operate within this period for complete SCI.⁵² Due to emerging evidence-based data and international consensus, patients who are medically stable and appropriate for surgery should be decompressed within 24 hours of injury.

Following determination of surgical candidacy, the approach to decompression should be considered. Surgical treatment of cervical spine injuries includes anterior, posterior, or combined anterior/posterior approaches. Proponents of an anterior approach advocate its safe positioning, surgical dissection along defined tissue planes, and ventral decompression performed under direct visu-

alization, while proponents of the posterior approach cite superior biomechanism and straightforward open reduction of facet dislocations.⁵³ Several studies have compared the two approaches; most of them indicated that there were no significant differences in outcome between the two approaches.⁵³⁻⁵⁷ In a prospective randomized study in 2003, 52 patients with unstable cervical spine injuries were randomized to receive either anterior or posterior stabilization and fusion.⁵⁷ Patients in these two groups reported no difference in neurologic outcome, fusion status, changes in alignment, and pain at final follow-up. Another prospective controlled trial in 2007 randomized 42 patients with unilateral cervical facet fractures to receive anterior or posterior fixation.⁵⁸ Anteriorly treated patients exhibited somewhat less postoperative pain, a lower rate of wound infection, a higher rate of radiographically demonstrated union, and better radiographically proven alignment, but reported a risk of dysphagia in the early postoperative period. Patient-reported outcome measures did not reveal a difference between anterior and posterior fixation procedures.

Following the development of the SLIC classification, a surgical approach and treatment algorithm for subaxial cervical SCI was published by Dvorak et al.⁵⁹ Operative cervical spine injuries were categorized into three morphologic subgroups consisting of burst fractures, hyperextension injuries, and translational/rotational injuries. According to this algorithm, burst fractures would benefit from a cervical vertebrectomy with autologous or allogenic bone graft, supplemented with an anterior cervical plate. When this scenario is accompanied by SCI and attendant spinal cord compression, any retropulsed fragments can be directly visualized and removed using this approach. For hyperextension injury, with or without avulsion fractures, an anterior cervical discectomy and fusion with a supplemental anterior plate is the recommended approach. Patients with ankylosing spondylitis or DISH would benefit from supplementation with posterior long-segment instrumentation and fusion due to failure rate of up to 50% in standalone anterior instrumentation and fusion procedures.⁶⁰ The most complex and unstable group is those with translation or rotation injuries. Although many of the compression and distraction injuries can be managed with anterior surgery alone, injuries in the translation or rotation category are more commonly treated with posterior and circumferential fusion. Many of the most unstable injuries, such as teardrop fractures or bilateral facet fracture dislocations, in which either

closed or anterior open reduction are not successful in achieving anatomic reduction, are best managed with a circumferential anterior and posterior fusion. Less severe injuries such as the unilateral facet fracture dislocation may be managed with either posterior or anterior approaches alone.

In thoracolumbar spine trauma, Vaccaro et al. suggested that the decision between an anterior, posterior, and combined anterior/posterior approach depends on the neurologic status of the patient and the integrity of the PLC.⁴³ For SCI patients with anterior compression of the spinal cord and an intact PLC, an anterior operation is appropriate to optimize the degree of decompression achieved, and potentially the degree of neurologic recovery seen at follow-up. If the patient has disrupted PLC in the absence of SCI, a posterior operation can be used to restore the posterior tension band and to re-establish stability. If, however, SCI and PLC disruption is present concurrently, this situation demands first an anterior decompressive procedure, followed by a posterior stabilization. In addition, based on data from 28 patients with three-column thoracolumbar injuries, McCormack developed the load sharing classification to grade (1) the amount of damaged vertebral body, (2) the spread of the fragments in the fracture site, and (3) the amount of corrected traumatic kyphosis.⁶¹ The system identified preoperative predictors of screw breakage when short segment, posterior-placed pedicle screw implants are being used, and evaluated the need for supplemental placement of anterior strut graft.

■ TRACTION/REDUCTION OF CERVICAL SPINE INJURIES

While cervical facet dislocations constitute only about 10–15% of all cases of cervical spine trauma, the results can be particularly devastating, with approximately 37% of patients with unilateral dislocation and 90% of patients with bilateral dislocation presenting with neurological deficit.⁶²⁻⁶⁴ The immediate treatment goals include restoration of anatomical alignment and immobilization of the cervical spine to prevent further SCI and to facilitate bone healing. In light of existing class III evidence suggesting improved neurological outcomes, the AANS/CNS recommends early reduction of cervical spinal facet fractures and dislocation injuries in awake and alert patients who can undergo serial monitoring.⁶⁵

Closed reduction can be achieved through the application of traction (Gardner-Wells tongs or Halo Ring) or manipulation under anesthesia (MUA). Starting at approximately 3 lb per number of vertebrae rostral to the level of the injury, weight is then added in an incremental fashion until radiologic reduction is achieved or until reduction fails (new or worsening neurological deficit, medical instability, radiologic evidence of over distraction or patient/equipment unable to tolerate additional weight). Closed reduction of fracture/dislocation injuries by traction-reduction appears to be effective and safer than MUA. Multiple retrospective analyses demonstrated closed reduction to have an efficacy of 80%, with less than 1% of patients experiencing a permanent neurological complication and 2–4% experiencing a transient neurological complication.⁶⁵

The utility of pre-reduction MRI to exclude traumatic disc herniation and potential cord compromise during the procedure is a controversial topic. The additional information provided by MRI is balanced by risks of transportation during an unstable period and a delay in treatment. Prospective reviews have shown that pre-reduction MRI will demonstrate disc herniation in one-third to

one-half of patients with acute cervical spinal facet subluxation injuries. However, this is of ambiguous clinical value, as there is a lack of correlation between these MRI findings and neurological deterioration. MRI prior to closed traction-reduction in patients with acute cervical fracture dislocation injuries is not routinely required, but is recommended before either anterior or posterior surgical procedures when closed reduction has failed.⁶⁵

■ PHARMACOLOGIC MANAGEMENT

Numerous neuroprotective agents have been investigated through animal experimentation and human clinical studies over the past few decades. Naloxone, thyrotropin releasing hormone (TRH), nimodipine, tirilazad mesylate, GM-1 ganglioside (Sygen), and corticosteroids have undergone human RCTs to investigate their safety and efficacy profiles (Table 56.5). Despite extensive clinical interest and research in this field, only corticosteroids have gained widespread, albeit controversial, indication for use in acute SCI.

Methylprednisolone sodium succinate (MPSS) is a synthetic glucocorticoid that has been extensively studied since the 1960s. Its proposed mechanisms of action include

Table 56.5: Landmark trials for therapies in the management of acute spinal cord injury.

Treatment	Trial	Year	Enrollment	Study design	Conclusions	Clinical use
<i>Pharmacotherapy</i>						
Naloxone	Flamm et al. ¹¹⁰	1985	29	Phase I— <i>pilot study</i>	No significant improvement in neurologic function	No
	Brckken et al. ⁶⁸ <i>NASCIS II</i>	1990	487	Phase III RCT	Unlike MPSS, no clinical benefit was ascribed to naloxone	
TRH	Pitts et al. ¹¹¹	1995	20	Phase II RCT— <i>pilot study</i>	No significant improvement in neurologic function	No
Nimodipine	Petitjean et al. ¹¹²	1998	106	Phase III RCT	No benefit can be ascribed to MPSS or nimodipine	No
Gacyclidine	Tadie et al. ¹¹³	1999	280	Phase II RCT	No significant improvement of motor recovery with incomplete cervical SCI	No
Tirilazad mesylate	Bracken et al. ¹¹⁴ <i>NASCIS III</i>	1997	499	Phase III RCT	No significant difference in neurologic recovery compared to MPSS	No
GM-1 ganglioside	Geisler et al. ⁷⁸	1991	37	Phase I RCT— <i>pilot study</i>	No significant improvement in neurological outcome	No
	Geisler et al. ⁷⁹ <i>The Sygen Multicenter Acute Spinal Cord Injury Study</i>	2001	797	Phase III RCT	No significant trend toward early recovery and neurological improvement	

Contd...

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<i>Treatment</i>	<i>Trial</i>	<i>Year</i>	<i>Enrollment</i>	<i>Study design</i>	<i>Conclusions</i>	<i>Clinical use</i>
MPSS	Bracken et al. ⁶⁷ <i>NASCIS I</i>	1984	330	Phase III RCT	No significant difference in neurologic outcome of high- and low-dose groups	Center and surgeon dependent
	Bracken et al. ⁶⁸ <i>NASCIS II</i>	1992	487	Phase III RCT	No significant difference in primary analysis <i>Post-hoc analysis:</i> significant improvement in motor recovery if MPSS is administered within 8 hour of injury	
	Bracken et al. ⁶⁹ <i>NASCIS III</i>	1997	499	Phase III RCT	<i>Post-hoc analysis:</i> significant improved neurologic outcome with 48-hour MPSS infusion for patients 3–8-hour post SCI	
	Otani et al. ¹¹⁵	1994	158	Phase III RCT	No significant difference in primary analysis	
	Petitjean et al. ¹¹²	1998	106	Phase III RCT	No benefit could be ascribed to MPSS or nimodipine	
<i>Evolving therapies</i>						
Riluzole	Fehlings et al. ⁸⁷ <i>NACTN for Treatment of Spinal Cord Injury</i>	2012	36	Phase I— <i>pilot study</i>	Promising preclinical data, pending final analysis	No
Minocycline	Casha et al. ⁸⁴	2012	52	Phase II RCT— <i>pilot study</i>	No significant motor improvement for cervical SCI, greatest difference in cervical motor-incomplete injury	No
Cethrin	Fehlings et al. ⁹⁰	2011	48	Phase I/II — <i>pilot study</i>	No significant motor improvement for complete cervical SCI	No
Therapeutic hypothermia	Dididze et al. ¹⁰⁶ <i>The Miami Project to Cure Paralysis</i>	2013	35	Phase I/II — <i>pilot study</i>	No significant improvement in motor function at 1 year following complete cervical SCI	No
	<i>ARCTIC</i>	2013	200 (proposed)	Phase II/III RCT (<i>pending approval</i>)	Future trial for efficacy and safety of modest hypothermia initiated within 6 hour of SCI	
CSF drainage	Kwon et al. ¹⁰⁹	2009	22	Phase I/II RCT — <i>pilot study</i>	Establishment of safety	No

(ARCTIC: Acute rapid cooling therapy for injuries of the spinal cord; CSF: Cerebrospinal fluid; MPSS: Methylprednisolone sodium succinate; NACTN: North American Clinical Trials Network; NASCIS: National acute spinal cord injury study; RCT: Randomized controlled trial; TRH: Thyrotropin releasing hormone).

attenuating neuronal membranes, decreasing tumor necrosis factor alpha release, improving spinal cord perfusion, and reducing neuronal calcium influx.⁶⁶ It has been investigated in a few human RCTs, including the landmark National Acute Spinal Cord Injury Study (NASCIS) I–III. Published in 1984, the NASCIS I trial compared

high- and low-dose MPSS regimen, administered for the first 10 days following SCI, without comparison to placebo.⁶⁷ At 6 months and 1-year follow-up, the two groups had similar neurologic outcomes, but the higher dose group had increased wound infection complication rates. Due to preclinical data suggesting that an even higher dose

of MPSS would be required for efficacy, the NASCIS II trial was completed in 1990 to investigate MPSS against naloxone and placebo.⁶⁸ The overall analysis did not show statistical significance, although the subgroup that received MPSS within 8 hours of injury revealed a modest but statistically significant motor and sensory improvement at 6 months, with persisting motor improvement at 1 year. This post hoc analysis finding led to the NASCIS III trial, which included SCI patients only within 8 hours of injury, to investigate the length of therapy and effects when coadministered with tirilazad mesylate, an aminosteroid with lipid peroxidation inhibiting properties.⁶⁹ The study compared the NASCIS II protocol of 24-hour administration protocol with a longer 48-hour protocol. Analysis of the results concluded that the 24-hour MPSS infusion was adequate for patients presenting within 3 hours of injury, but patients presenting 3–8 hours after injury would benefit from a longer course of infusion over 48 hours. Criticisms of the NASCIS trials point to the controversial data on corticosteroid benefits that were observed only in subgroup analysis. Furthermore, numerous prospective and retrospective analyses of MPSS administration for SCI revealed increased rates of wound infections, sepsis, pulmonary complications, gastrointestinal complications, urinary tract infections, and acute corticosteroid myopathy.^{70–75}

The 2013 AANS/CNS guidelines on the pharmacologic treatment of SCI do not recommend the routine use of MPSS due to lack of class I/II evidence.⁷⁶ However, in the context of inconsistent benefits, the role of corticosteroids in SCI continues to be controversial, heavily debated, and surgeon-dependent. It remains an option for nondiabetic and immunocompetent patients presenting within 8 hours of nonpenetrating SCI. As per NASCIS II/III protocol, patients presenting within 3 hours of injury should receive 30 mg/kg bolus followed by infusion at 5.4 mg/kg/h for 24 hours, while those presenting between 3 and 8 hours of injury would benefit from a longer infusion of 48 hours.

GM-1 ganglioside (Sygen) is a member of a heterogeneous family of complex glycosphingolipids, which are abundant naturally in neurons. In laboratory studies, Sygen reduces glutamate-mediated excitotoxicity and subsequent apoptosis, and also mimics endogenous neurotrophic factors, which stimulate nerve fiber growth and repair.⁷⁷ It has been explored as a therapy for multiple neurodegenerative diseases, yielding promising animal data. In 1991, a small phase II trial of GM-1 in SCI suggested improved neurological recovery.⁷⁸ The following year, the largest human phase III RCT for SCI to date, with an

enrollment of almost 800 participants, was initiated to evaluate the role of low-dose and high-dose Sygen against placebo.⁷⁹ Although a nonsignificant trend toward greater mobility on the Modified Benzel Walking Scale was noted at 6 months follow-up, no further investigations were completed and Sygen is not used clinically around the world.

EMERGING THERAPIES

To further understand and advance the field of SCI management, several novel treatments are currently undergoing investigation. Neuroprotective agents including minocycline, riluzole, and Cethrin, as well as techniques of CSF drainage and therapeutic hypothermia have shown efficacy in animal models and hold promise for human translation.

Minocycline is a synthetic tetracycline antibiotic and metalloproteinase inhibitor. It has been demonstrated in laboratory studies to have anti-inflammatory and anti-apoptotic properties, acting to suppress cytokine production, microglial activation, and neuronal death.^{80–83} The first human translation of this information was a single-center, double-blind RCT involving 52 patients who were either administered intravenous minocycline or placebo for 7 days. The results from this phase II study were published in 2012, and minocycline administration was associated with a tendency toward improvement across several outcome measures, approaching significance for motor improvement in the cervical incomplete SCI group.⁸⁴ These data are encouraging and provide foundation for future investigation.

Riluzole is a benzothiazole sodium channel blocker currently used to treat ALS.⁸⁵ It is believed to mitigate neurotoxic mechanisms by inhibiting presynaptic glutamate release and increasing high-affinity glutamate uptake, therefore reducing motor neuron degeneration.⁸⁶ A human trial has recently demonstrated its safety and promise, and a multicenter Phase II/III RCT examining its clinical translation is under way.⁸⁷

Cethrin[®] is a combination of fibrin sealant Tisseel[®] and Rho-inhibitor BA-210 that can be applied to the dura at the time of surgical decompression. Following SCI, myelin and extracellular matrix inhibitors trigger collapse of the growth cones of regenerating axons via the Rho pathway.⁸⁸ BA-210 is a bacterial-derived toxin and cell-permeable form of C3 transferase, which inhibits the Rho pathway, effectively antagonizing all known myelin and extracellular matrix inhibitors.⁸⁹ A phase I/IIa trial involved 37 com-

plete SCI patients who received intraoperative Cethrin an average of 53 hours following injury. At 6 months post injury, 27% of patients who received Cethrin improved by ≥ 1 ASIA grade, with no associated increase in complications.⁹⁰ A phase III RCT is being designed to investigate the role of Cethrin on a larger scale.

Stem cell therapy has garnered considerable attention in preclinical and human studies as a method of cell replacement in addition to preservation. Stem cells regulate gliosis and scar formation, prevent cyst formation, and enhance axon elongation.⁹¹ Through secretion of anti-apoptotic and proangiogenic neurotrophic factors, they also cultivate an environment supportive of neural plasticity and regeneration.⁸ In addition to supporting and preserving surviving cells, they also replace damaged neurons and glial cells, playing an important role in the restoration of neural circuitry by remyelination of surviving axons, and bridging of lesion cavities across gliotic and scarred tissues.⁹²

Bone marrow stromal cells, olfactory ensheathing cells, Schwann cells, activated autologous macrophages, human embryonic stem cells, and tissue-derived adult neural stem cells have all been studied in preclinical studies, with no type showing superiority.⁹¹ More than a dozen human trials have begun with these stem cell types for treatment of both acute and chronic SCI.^{8,47} Prior to widespread translation of this therapy, challenges regarding their propensity for tumor formation, creation of abnormal circuitry leading to dysfunction, and the ethical dilemma surrounding their harvesting and use must be overcome.⁹¹ The development of induced pluripotent stem cells in 2006 allows any adult somatic cell type to be transformed into an embryonic stem cell through the introduction of four genes (Sox2, klf4, c-Myc, and Oct4).⁹³ This technology has been an important breakthrough as it avoids ethical issues inherent to fetal cell sources and also allows for autotransplantation obviating the need for immunosuppressants. Extensive ongoing research continues to contribute to our knowledge of the properties of stem cells, and their role in both host interaction and regenerative potential.

Therapeutic hypothermia has been intensively studied in animal models and human conditions of cardiac arrest and TBI.⁹⁴ Laboratory investigations have demonstrated that hypothermia reduces cellular energy requirements, slows enzymatic activity, and decreases cerebral metabolic rate and glucose requirements.^{95,96} Hypothermia for animal models of SCI exhibited an association with attenuated glutamate excitotoxicity, decreased polymorphonuclear

leukocyte invasion and neuroinflammatory response, and reduced vasogenic edema and hemorrhage at the primary site of injury.⁹⁷⁻¹⁰⁵ Interest in human translation of this information led to a phase II single-center study on the efficacy and complications of hypothermia for acute complete cervical SCI.¹⁰⁶ A total of 14 patients with complete SCI were recruited and moderate systemic hypothermia of 33°C was achieved in all patients for the first 48 hours of injury. Neurologic outcome was matched to data from historical cohorts. Recently completed, the study showed no increase in complications associated with hypothermia. A phase III RCT is being planned and designed to investigate hypothermia in a larger, multi-center level.

Cerebrospinal fluid drainage is a technique to lower intrathecal pressure, and is routinely performed in thoracoabdominal aortic aneurysm surgery to prevent spinal cord ischemia and paraplegia.^{107,108} In SCI, it is believed to increase spinal cord perfusion pressure, attenuate ischemia and provide neuroprotection. A phase I/II trial involving 22 patients was completed to study intrathecal pressure changes before and after surgical decompression, as well as to evaluate its safety, feasibility, and efficacy.¹⁰⁹ CSF drainage was not associated with adverse effects; however, in this underpowered study, neurologic improvement was not observed.

CONCLUSION

The initial assessment and acute management of SCI play a key role in stabilizing patient's clinical status, mitigating secondary injury, and improving long-term survival and neurologic outcomes. Initial management should focus on early spinal immobilization, treatment of respiratory distress and hemodynamic instability, and admission to an intensive care setting for monitoring. Due to the physiologic complexity of acute SCI, the treatment regimen should consist of a comprehensive combination of closed or open decompression and neuroprotective pharmacologic therapy targeting various stages of the primary and secondary injury cascade. For appropriate surgical candidates who are medically stable, surgery should be performed within 24 hours of SCI to establish normal spinal anatomy and decompression. Corticosteroid administration within 8 hours of SCI remains a controversial topic, and any benefit is balanced by pulmonary, infectious and wound healing complications. Lastly, multiple neuroprotective agents and treatment modalities including

CSF drainage and therapeutic hypothermia demonstrate highly encouraging preliminary laboratory and phase I/II data, and lay the foundation for future investigation and possible incorporation into clinical treatment.

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Pharmacology and Timing of Surgical Intervention for Spinal Cord Injury

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Snapshot

- » Pharmacologic Neuroprotective Therapies after Acute SCI
- » Cellular Therapies for Acute tSCI
- » Timing of Surgical Intervention in Acute SCI

BACKGROUND

Traumatic spinal cord injury (tSCI) is not only devastating for patients and their families, but it is also associated with tremendous societal impact. In North America, the incidence of spinal cord injury (SCI) varies geographically between 27 and 48.4 cases per million individuals.^{1,3,5,7,9,11} The average lifetime costs of care range between 1.47 million and 3.03 million in Canadian dollars.^{12,13} These injuries impose a substantial toll on the individual and lead to increased healthcare utilization, lower rates of social participation, and lower rates of employment than the uninjured population.

Despite the significance of this type of injury to individuals, their families, and society as a whole, there are no clearly accepted and proven treatments to reduce the severity of tSCI, nor is there any proven regenerative or curative therapy available. This leaves caregivers with the unenviable task of explaining that all we can do is simply support the natural recovery of the spinal cord by optimizing the environment around it (surgical stabilization and decompression) and supporting its general physiological functions (perfusion, oxygenation). When the patient and their family ask “what can you do, Doctor, to repair this injured spinal cord?” the honest answer is “very little, beyond encouraging optimal natural recovery.”

PHARMACOLOGIC NEUROPROTECTIVE THERAPIES AFTER ACUTE SCI

The pharmacological neuroprotection of a potentially injured spine and spinal cord begins at the accident scene, where the immediate goal is to extract the patient from any imminent danger and ensure that fundamental aspects of resuscitation at the scene are performed. This may involve elements of both basic life support (BLS) and advanced life support (ALS). BLS involves noninvasive therapies such as spinal immobilization and external protection of the airway, while ALS adds intubation and assisted ventilation, as well as intravenous fluid and medication administration. Intravenous fluids are frequently administered at the scene of injury and inotropic support for maintaining blood pressure may also be initiated prior, or on the way, to a specialized SCI center. Unstable patients may have to be diverted to the nearest regional center where they can be stabilized and then be transported, when hemodynamically and physiologically stable, to a tertiary care center.

By maintaining oxygenation and perfusion, the goal is to minimize any further neurologic injury. In developing countries, it is likely that many tSCIs either develop or deteriorate during extraction and transport to medical facilities possibly due to either lack of recognition, lack of immobilization or failure to provide cardiorespiratory

support. Periods of profound hypotension, bradycardia, and hypoxemia that often can occur at the scene of the injury and in subsequent hours likely inhibit natural recovery of the tSCI and at worst, may lead to progression of the extent and severity of the neurological injury. Rapid transport time to a definitive center of excellence in tSCI care is associated with improved neurological and overall function.^{20,22}

Hypotension in the acute trauma patient is assumed to be of a hemorrhagic etiology until proven otherwise. The chest, abdomen, and pelvis should be examined, as they are the most likely sources of blood loss. Hypotension in the presence of bradycardia without any overt signs of blood loss likely signifies neurogenic shock, typically seen in SCIs that occur cephalad to T4. Although no universally accepted hemodynamic parameters define neurogenic shock, most studies use a systolic blood pressure <100 mm Hg and define bradycardia as a heart rate of <50 beats per minute in patients without any other cause of shock.²³

Regardless of its etiology, hypotension must be aggressively corrected to minimize secondary ischemic damage to the spinal cord. In patients whose blood pressure is unresponsive to crystalloid, universal donor blood group (group O, Rh negative) is recommended until matched blood products are available. Early administration of blood products is of particular importance in spinal cord injured patients to maximize the oxygen-carrying capacity, thereby minimizing the secondary ischemic and hypoxic injury to the vulnerable cord.²⁴ Invasive monitoring from arterial and central venous access is imperative to guide interventions. Once the patient is normovolemic, the maintenance of a mean arterial pressure (MAP) of 85–90 mm Hg is recommended for 5–7 days, although it is recognized that the clinical evidence to support this target MAP is relatively weak.^{27,28} Ongoing hypotension can be managed with vasopressors such as dopamine, norepinephrine, or phenylephrine, whose agonist activity raises the systemic vascular resistance. This can be followed by the oral agonist midodrine, which can be weaned over a couple of weeks as hemodynamic stability is achieved. Low cardiac output resulting from persistent bradycardia can be treated with atropine.

When a tSCI occurs, the spinal cord undergoes two types of insults referred to as the primary and secondary injuries. The primary injury, sustained from the initial trauma, and resulting spinal cord compression, initiates a cascade of local and systemic factors that lead to ischemia, inflammation, production of free radicals, increase in

membrane permeability, loss of autoregulation, and pathologic electrolyte shifts, all of which can profoundly modulate the extent of injury from the initial mechanical stress.²⁹ This cascade of events is known as the secondary injury. It develops over minutes to weeks following trauma, and is where the opportunity for neuroprotection and therapeutic intervention lie.^{29,31}

Methylprednisolone

One of the most tragic examples of our failure to effectively translate potentially promising neuroprotective preclinical findings into clinical practice is the tale of methylprednisolone. Methylprednisolone sodium succinate (MPSS) is a pharmacological neuroprotective agent that is administered intravenously. This steroid has been studied extensively in animal models, and has been reported to act through a number of different mechanisms, including the reduction of lipid peroxidation, improvement in spinal cord blood flow, and attenuation of inflammation.^{29,32,34,35}

The administration of MPSS to acute SCI patients was tested in three large-scale prospective randomized double-blinded multicenter clinical trials: the National Acute Spinal Cord Injury Studies (NASCIS) I, II, and III.^{36,38,39} The first study failed to reveal any neurological improvements with MPSS, and it was later suggested from animal studies that this was due to the administration of subtherapeutic doses. In the NASCIS II trial, the dose was increased to a 5.4 mg/kg bolus, followed 45 minutes later by a 24-hour infusion of 30 mg/kg. This second study again reported a negative primary outcome; however, upon post hoc analyses, the authors reported that patients treated within 8 hours from the time of injury experienced significant motor and sensory improvements. MPSS rapidly became a standard of care in the treatment of acute tSCI following the release of the NASCIS II results to the media and publication in a high impact journal.³⁶ Unfortunately, a lack of appropriate scrutiny through the peer review and editorial review processes led to a debate in the literature, ambiguity and the eventual repudiation of recommendations for the use of this drug.^{1–11} The NASCIS III study refined the administration protocol by reporting greater motor and functional improvement when the infusion was extended to a 48-hour period in patients whose treatment was initiated 3–8 hours post injury (24-hour infusion was shown to be equivalent for those treated at less than 3 hours post injury). The longer infusion time did, however increase the incidence of severe sepsis and pneumonia.

The NASCIS trials have been heavily criticized for methodological issues including inadequacies in randomization (e.g. large difference in severity of neurologic deficits for patients in each treatment arms), deficiencies in statistical analyses (e.g. arbitrary 8-hour time window suspected to have been decided after a post hoc analysis), and poorly defined clinical end points (scoring of motor improvements not clinically relevant).^{2,4,8,10,12,13} Numerous societies have performed exhaustive reviews of the NASCIS trials and other human SCI studies, and have concluded that MPSS should not be considered a standard of care, but rather a treatment option.¹⁴⁻¹⁷ The majority of Canadian surgeons have since abandoned the use of MPSS, although its use in the United States continues, in large part due to the medicolegal climate and fears of litigation.^{18,19} This issue therefore is not resolved and remains a glaring example of how tSCI clinical trials that intend to further therapeutic alternatives can profoundly frustrate and potentially harm the care of patients. In fact, the increased risk of mortality when MPSS is used in acute head injury has been demonstrated in the corticosteroid randomisation after significant head injury (CRASH) trial.²⁰⁻²² The identification of this substantial risk profile for MPSS when used in traumatic head injury has led to newly published guidelines discouraging the use of MPSS in SCI.^{17,23}

Minocycline

Minocycline is a tetracycline antibiotic that has been used clinically for many years for other indications. It is thought that minocycline increases interleukin-10 and decreases tumor necrosis factor alpha expression, preventing the exacerbation of the secondary injury in SCI by attenuating neuroinflammation and inhibiting apoptosis.²⁴⁻²⁶ Other proposed mechanisms of action include the inhibition of excitotoxicity, oxidative stress, apoptotic pathways, and inflammatory mediators released by activated microglia.^{25,27,28} Minocycline has also been reported to reduce microglial activation.^{25,29}

In animal models, minocycline has been shown to improve neurological and histological outcomes, reduce neuronal and oligodendroglial apoptosis, decrease microglial activation and reduce inflammation.²⁹⁻³¹ Reduced tissue damage, lesion size and apoptosis at the site of injury have been correlated to improved functional outcomes.^{26,29,32-35}

A recent phase II placebo-controlled randomized trial of minocycline in acute traumatic SCI patients has demonstrated its safety.³⁶⁻³⁹ Improvement in some subgroups of

patients, particularly cervical incomplete injuries, has been encouraging. A multicenter phase II clinical trial has been initiated in Canada.

Riluzole

Riluzole is a benzothiazole anticonvulsant that is currently approved by the FDA for use as a neuroprotective agent in amyotrophic lateral sclerosis. It functions as a sodium channel blocker that attenuates secondary damage by decreasing intracellular sodium and inhibiting presynaptic calcium-dependent glutamate release. In animal models, it has been shown to increase sparing of gray matter and improve locomotor function. A recently published prospective, multicenter phase I trial, was undertaken by the North American Clinical Trials Network to investigate the pharmacokinetics, safety, and to obtain pilot data on the effects of riluzole on neurological outcome in acute tSCI. This study demonstrated the drug's safety and again provided promising findings of neurological recovery.^{36,40} A prospective multicenter clinical trial has been initiated.⁴¹

Erythropoietin

Erythropoietin (EPO) is a glycoprotein hormone that has a hematopoietic effect that results in increased red blood cell production. Erythropoietin is administered in intravenous and subcutaneous preparations and is reported to promote tissue protection in response to hypoxia and improve locomotor performance in animal models.⁴² A single dose of EPO immediately after SCI improved motor function recovery, decreased lesion severity, and increased neuronal regeneration in a rat contusion model of SCI.⁴³ EPO has also been shown to have anti-inflammatory, antioxidant, and antiapoptotic properties.⁴² A small multicenter comparative study of EPO and methylprednisolone in patients with severe motor complete tSCI began in 2008. Recruitment of subjects for this study, however, was aborted at the time of this writing.⁴⁴

Magnesium

Magnesium acts as an N-methyl-D-aspartate receptor antagonist. It is thought to attenuate excitotoxicity by limiting free radical production and glutamate release, and reduces apoptosis.⁴⁵ High-dose magnesium administration after SCI resulted in significant functional recovery, reduction in apoptosis, and lipid peroxidation.⁴⁶ A combination of magnesium and polyethylene glycol has been developed for administration to humans with SCI,

allowing lower doses to be administered.⁴⁷ A phase I study of polyethylene glycol and magnesium in healthy human volunteers has been completed but not published. A phase II study in cervical SCI patients was initiated in 2013.

Nogo-A Antibodies

Anti-Nogo-A antibodies are directed against molecules that inhibit neurite regrowth. Specifically, they are felt to inhibit the activity of Nogo-A, an inhibitory constituent within central nervous system (CNS) myelin that impedes axonal regeneration and/or sprouting. There has been a nonrandomized, multicenter clinical trial in patients with ASIA A thoracic and cervical SCI completed in Switzerland. Treatment was initiated between 7 and 14 days post injury. Antibody was administered by means of an intrathecal infusion over weeks, or by repeated bolus intrathecal injections. A study began in 2006 and was completed in 2011. No results were published at the time of this writing.⁴⁸

CELLULAR THERAPIES FOR ACUTE tSCI

Cell transplantation into the injured spinal cord is another area of significant research interest. Cells transplanted into the spinal cord may play a number of potential neuroreparative roles. For example, they may secrete neurotrophic factors and create a permissive environment for axonal sprouting/regeneration by “bridging” the injury site, or they may remyelinate demyelinated (but otherwise intact) axons to improve signal transduction across the injury.

The use of stem cell technology has created much excitement within the SCI field, as the ability to differentiate them into many different cell types raises the potential for them to even replace lost neurons and regenerate axons that might act as “relays” across the injury site.⁴⁹

A large variety of cell substrates have shown promise in preclinical models of SCI, including Schwann cells, olfactory ensheathing cells, mesenchymal stem cells, neural stem cells, and embryonic stem cells.⁵⁰ A clinical trial of oligodendrocyte progenitor cells, derived from human embryonic stem cells, was initiated in October 2010 by Geron Corporation (Menlo Park, CA); however, the trial was halted just over a year later due to financial considerations after enrolling five patients. A clinical trial of neural stem cells was initiated in Zurich, Switzerland, sponsored by Stem Cells, Inc., and at the time of this writing had enrolled four patients. A clinical trial of Schwann cells has recently been initiated by the Miami Project to cure paralysis. Like

the pharmacologic treatments, it will still take many years before evidence of efficacy will be established in such clinical trials of cell transplantation therapies.

Autologous Incubated Macrophages (Proneuron)

In response to injury, the macrophage-mediated immune response is reduced in the CNS as compared with the more actively regenerative peripheral nervous system. It was thought that manipulation of macrophage activation by monocyte cocubation with peripheral nervous system tissue would potentially facilitate neural regeneration. Rodent studies suggested improved regeneration of nerves exposed to macrophages, activated by incubation with peripheral nerves.

A clinical trial to determine the efficacy and safety of autologous incubated macrophage treatment enrolled eight participants with complete SCI who were treated with autologous macrophages, which were prepared by cocubating peripheral blood monocytes with harvested autologous skin. This study failed to show a significant difference in primary outcome between the two groups. In fact, the control group demonstrated superior neurological conversion rates.

TIMING OF SURGICAL INTERVENTION IN ACUTE SCI

Based on the pathophysiology of secondary injury after acute SCI, it is intuitive to think that early decompression of the spinal cord would be an effective neuroprotective strategy. Many animal studies have demonstrated that early decompressive surgery diminishes the extent of secondary injury and improves neurological outcomes, although the majority of these studies have utilized models of low velocity compression rather than the more clinically relevant high-velocity contusion.⁵¹⁻⁵⁴ Some have even noted that this benefit is inversely proportional to the time from injury to decompression.^{54,55} Despite this, it has been difficult to demonstrate in clinical studies of human SCI a significant neurologic benefit that results from early surgical decompression. There are many potential reasons for this. Firstly, human injuries occur with considerably higher and faster biomechanical forces than are simulated in animal studies, and hence the primary injury in humans is likely to be more severe and leave less tissue amenable to the neuroprotective benefits of surgical decompression.

Secondly, the definition of what constitutes “early surgical decompression” has not been well established, and even today there remains wide variability in the time at which SCI patients have surgery.

There are large practical difficulties in designing and executing a study, in which timing of surgery can be evaluated, as most clinicians would be unwilling to randomize a patient to a later decompression, when earlier surgery is feasible and practical. Patients are not likely to agree to be randomized to either early or late surgery. In an international survey of spine surgeons, over 80% of the respondents indicated a preference to surgically decompress the spinal cord within 24 hours and thus, there is a profound lack of clinical equipoise in relation to timing of surgery. In fact, for an incomplete cervical SCI, 72.9% of respondents felt that decompression should be achieved within 6 hours, while 46.2% felt that this sort of early decompression should be achieved for complete cervical SCI as well.⁵⁶

Recently, the Surgical Timing in Acute Spinal Cord Injury Study (STASCIS) was published,⁵⁷ which represents the largest prospective multicenter cohort study comparing the neurologic outcomes of patients with cervical SCI receiving “early” (<24 hours) versus “late” (over 24 hours) surgical decompression. The 313 patients enrolled were not randomized to a specific treatment arm. Instead, the decision of surgical timing was left to the enrolling surgeons and was often dependent on the individual’s circumstances (time for transfer to hospital, time required to obtain adequate imaging, and discretion of the attending spinal surgeon). 19.8% of patients in the early decompression cohort showed a ≥ 2 AIS grade improvement compared to 8.8% in the late decompression group. After a multivariate analysis was performed to account for preoperative neurological status and steroid administration in both groups, the odds of having two or more AIS grades of improvement were 2.8 times higher in those who were decompressed early. The secondary outcomes consisted of in-hospital postoperative complication rates and mortality: the early group experienced a complication rate of 24.2% compared to 30.5% in the late surgery group. When the complications data are looked at more closely, “construct failure requiring surgery” is reported to have occurred in 6.3% versus 2% of cases in early versus late surgery, respectively, which likely relates to the lack of specific equipment and experienced personnel when surgery is expedited. One death occurred in each group in the 30-day post-injury period. Of note, the STASCIS study excluded patients with severe concomitant injuries and was restricted to cervical injuries.⁵⁷

A recent systematic review and meta-analysis of the timing to surgery has been published and suggests that early surgery performed up to 24–72 hours after injury was associated with an almost six motor point improvement when compared to surgery performed later. There was a longer length of hospital stay associated with late surgery. The authors caution that these results are not robust and should be interpreted cautiously.⁵⁸

SUMMARY

Intensive scientific research has shed light on the complex pathophysiology of SCI, and has led to the development of a number of experimental treatments that are under evaluation in clinical trials. Although no pharmacologic neuroprotective or neuroregenerative therapies have been validated for clinical use, there are some promising investigations underway.

Likely, some form of combinatorial therapy that includes pharmacologic interventions at specific time points following injury as well as best clinical practices, such as hemodynamic support, may ultimately benefit patients.

For the time being, it appears to be clear that there is no dramatic detriment to early surgery from either a neurological outcome or a health systems perspective. When it is feasible to do so, and the resources are available and the system of care permits it, early surgical intervention should be encouraged.

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Pediatric Spine Trauma and Spinal Cord Injury

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Snapshot

- » Introduction and Epidemiology
- » Anatomical Considerations

- » Patterns of Injury and Treatment Recommendations

INTRODUCTION AND EPIDEMIOLOGY

Spine trauma and spinal cord injury (SCI) is relatively rare in the pediatric population. In the United States, <4% of SCI occur in patients younger than 15 years of age.¹ Cervical spine trauma is responsible for 60–80% of pediatric SCI and results in significant lifelong disability and healthcare cost.² The incidence of SCI in the United States between the years of 1997 and 2000 was 1.99 per 100,000 children, compared to 1 per 1 million children in Canada.^{3,4} This translates to approximately 1,455 new SCI in pediatric patients per year in the United States.⁴ Boys are more than twice as likely than girls to suffer an SCI, and Asian children have the lowest incidence of SCI (0.36/100,000) compared to African American children who have the highest (1.53/100,000). Children younger than 11 years of age with a neurological injury secondary to cervical spine trauma have a 5.1 times higher risk of death than do patients older than 11.⁵

A study of 103 consecutive pediatric patients with cervical SCI found that motor vehicle accidents were the most common mechanism of injury representing 52% of all patients.⁶ Of the 18.5% of the children who presented with fatal SCI, 95% of the injuries were the result of motor vehicle accidents.⁶ Interestingly, seat belts do not appear protective for pediatric SCI.⁷ Sport injuries were the second most common etiology, accounting for 27% of patients. American Football has been the subject of much attention, both in the lay press and academic literature, as an etiology

of SCI in the pediatric population. In 2010, there were seven permanent SCI associated with American Football, five in the high school population and two in collegiate athletes.⁸

The rule changes adopted in 1976 that banned spear tackling have been associated with an overall decrease in SCI in American Football.⁹ In 2010, the overall risk of cervical SCI in high school and college football players was 0.33 and 2.66 per 100,000 participants, respectively. Despite the focus on American Football as an etiology of athletic SCI, recreational diving is probably a more common cause of sport-associated SCI; in one study, SCI resulting from recreational aquatics represented 66% of all athletic SCI compared to only 6% from football.⁹ Similarly, nearly twice as many cervical spine fractures and dislocations were caused by diving compared to football¹⁰ in a retrospective study of 41 years of data from the Mayo Clinic.⁵

Child abuse is a rare cause of SCI, and is typically seen in infants and young children. Spinal cord injury resulting from child abuse is frequently associated with head injuries and with multiple extremity fractures.¹⁰

ANATOMICAL CONSIDERATIONS

Because of anatomical differences, injuries to the occipital-cervical complex (OCC)—i.e. the occiput-C1-C2—appear to be more common in children than adults. Compared to adults, children not only have an increased ratio of head to

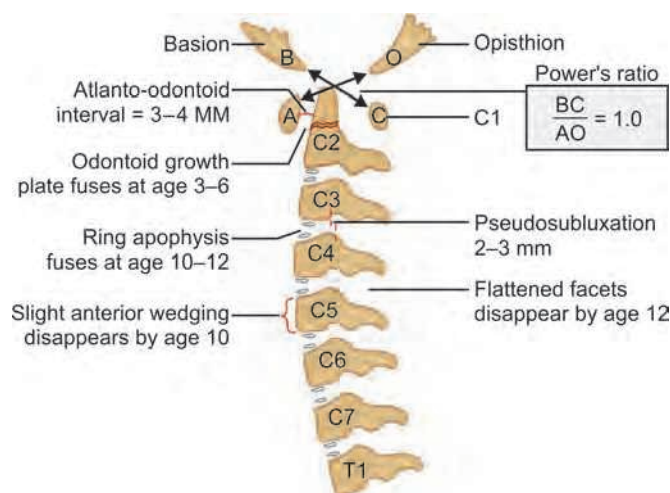


Fig. 58.1: Anatomical differences observed in plain radiographs in the pediatric spine.

body mass and flatter slope of the C1 superior facet joints, but also have increased ligamentous laxity and decreased posterior musculature, all of which contribute to the preponderance of upper cervical spine injuries in children (Fig. 58.1).^{11,12} Ligaments, including the transverse ligament of the atlas, alar and apical ligaments, and the tectorial membrane, are the primary stabilizers of OCC, and atlanto-occipital dissociation (AOD) results from their disruption. Upper cervical spine injuries in children are associated with increased rates of mortality.¹³ Figure 58.1 illustrates unique radiographic features of the cervical spine; note that a Power's ratio >1 is suggestive of anterior AOD.

There is a significant mismatch between the elasticity of the pediatric spinal column and the spinal cord. In a cadaveric study, Leventhal found that the spinal column of a newborn could be stretched 2 inches, while the spinal cord itself could only stretch 0.25 inches before rupture.¹⁴ This anatomical difference is hypothesized to be responsible for the increased incidence of spinal cord injury without radiographic abnormality (SCIWORA) in children, accounting for up to one third of SCI in the pediatric population.³ It is important to recognize that SCIWORA, as originally described, did not include the use of magnetic resonance imaging (MRI).^{14,15} Although MRI can frequently identify ligamentous injuries in patients with SCIs, it is still not 100% sensitive, and reports of patients with complete spinal cord transection with normal extraneural findings can be found.¹⁶ Severe SCIWORA generally has a poor prognosis for recovery and bracing has been shown to have little benefit.¹⁷ Given that MRI has

become the standard of care in the evaluation of patients with SCI, for the remainder of this chapter the term SCIWORA will refer to patients with no evidence of extraneural injury on any imaging modality, including MRI.

The disks of the pediatric spine are more resistant to injury than the vertebral bodies.¹⁸ The occurrence of traumatic intraosseous disc herniations, i.e. Schmorl's nodes, reveals the greater strength of the annulus fibrosis compared to the cartilaginous endplate. The more resilient disks in children permit the distribution of compressive forces over multiple levels, leading to the observation of multilevel compression fractures in children.¹⁹

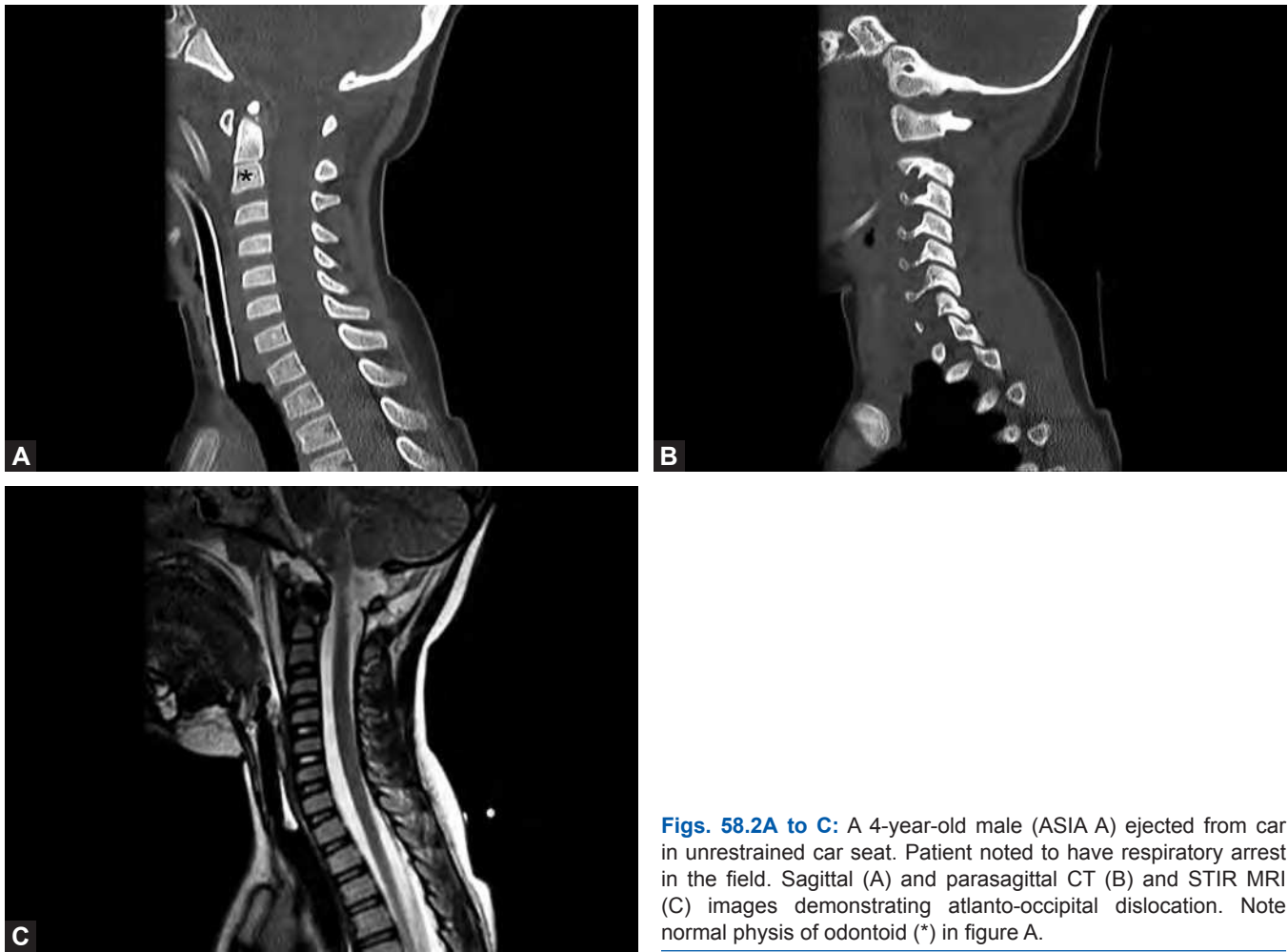
Although it is commonly held that children have an inherently better capability of recovering from neurological injury than adults, this has not been clearly demonstrated in the literature. As in adults, the final neurological outcome is most dependent on the extent of injury. Incomplete injuries have a better prognosis for recovery than complete injuries.³ A recent review by Parent et al. concluded that the evidence of superior neurological recovery in children was "very slight."¹³

Scoliosis following pediatric SCI is commonly observed, and is thought to be secondary to loss of trunk muscle control. The reported incidence of scoliosis following pediatric SCI varies in the literature from 23% to 97%,^{20,21} although the rate is clearly greater than the 5% incidence of post-SCI scoliosis observed in adults.²⁰ Children who have not undergone their pubertal growth spurt at the time of SCI have the highest rate of scoliosis, approaching 100%.²¹ The pattern of curvature in post-SCI scoliosis is similar to that observed in other cases of neuromuscular scoliosis.

PATTERNS OF INJURY AND TREATMENT RECOMMENDATIONS

Atlanto-Occipital Dissociation

Historically, these injuries were almost universally fatal because of high cervical spinal cord/brainstem injury and resultant respiratory arrest. Hypoxia secondary to brainstem or high cervical cord injury also portends a poor prognosis. With modern Advanced Trauma Life Support protocols, specifically on-site intubation, cervical spine immobilization, and ventilator support, more children are surviving these injuries. A 2003 review of the literature found evidence of 41 children surviving for >48 hours after recognized AOD. Despite the severity of these injuries, there are case reports of preservation of neurological function after AOD.^{22,23}



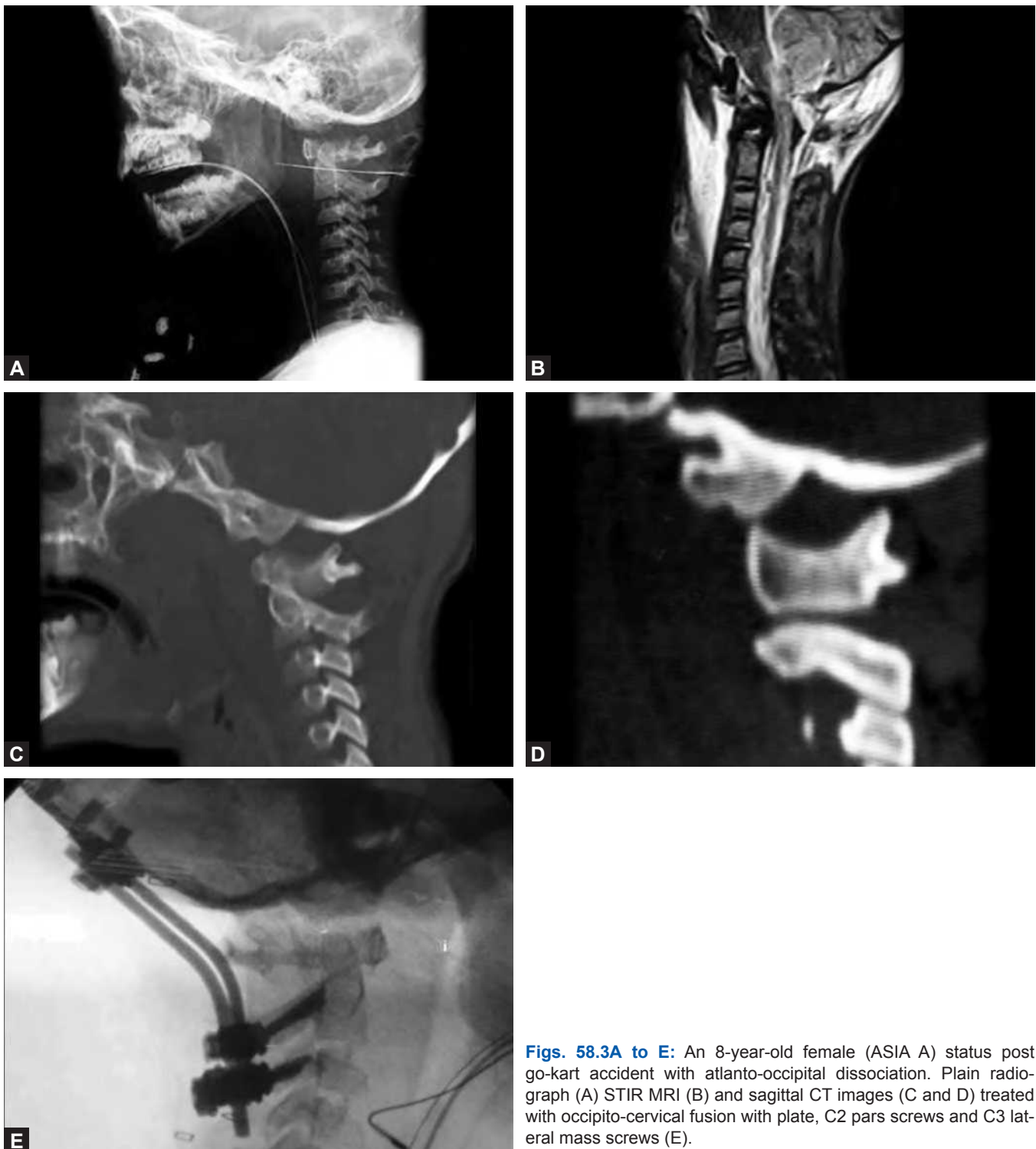
Figs. 58.2A to C: A 4-year-old male (ASIA A) ejected from car in unrestrained car seat. Patient noted to have respiratory arrest in the field. Sagittal (A) and parasagittal CT (B) and STIR MRI (C) images demonstrating atlanto-occipital dislocation. Note normal physis of odontoid (*) in figure A.

The first step in treating a child with AOD is to recognize the injury. This requires a high index of suspicion, as up to one third of children with AOD may not be identified during initial evaluation;²⁴ this number may be even greater than that in adults.²⁵ Children with AOD are usually the victims of high-energy motor vehicle accidents (Figs. 58.2 and 58.3). Lack of respiratory drive is a clue to high cervical spine injury, although the patients are commonly intubated on scene. Concomitant head injury is common and may obscure the diagnosis. Cranial nerve palsies, especially involving VI, and IX–XII may be seen.^{24,25}

The use of traction is contraindicated and a properly sized rigid pediatric cervical collar is essential, and must be applied carefully so that no distractive forces are applied to the spine. If AOD is recognized in a pediatric trauma patient, the authors recommend immediate reassessment of cervical spine immobilization. The use of specialized pediatric backboards with a recess to accommodate the

proportionally larger occiput of a child prevents relative flexion of the upper cervical spine (Fig. 58.4). Taping the child's head to the backboard with sandbags used as bolsters to immobilize the cervical spine may be the most efficacious way to ensure the head and cervical spine are immobilized until a halo thoracic vest can be placed. The use of methylprednisolone in SCI continues to be controversial. The National Acute Spinal Cord Injury Study trials specifically excluded patients younger than 14 from their studies.

When electing to pursue halo vest treatment in children, the placement of the vest is different than adults. More pins are typically used and they are tightened to a lower torque. For children aged 3 and younger, the use of up to 12 pins, tightened to 2 inch-pounds of torque has been described.²⁶ For children aged 4–10 years, the authors recommend the use of six to eight pins tightened to 2 inch-pounds of torque. For patients between 10 and 15 years, the authors recommend



Figs. 58.3A to E: An 8-year-old female (ASIA A) status post go-kart accident with atlanto-occipital dissociation. Plain radiograph (A) STIR MRI (B) and sagittal CT images (C and D) treated with occipito-cervical fusion with plate, C2 pars screws and C3 lateral mass screws (E).

four to six pins tightened to 6 inch-pounds, and for patients 15 years and older, four pins tightened to 8 inch-pounds are used. The authors strongly recommend placement of a halo

vest in the operating room with sedation, as well as having a C-arm available and positioned so that lateral radiographs may be taken to evaluate for reduction.¹¹

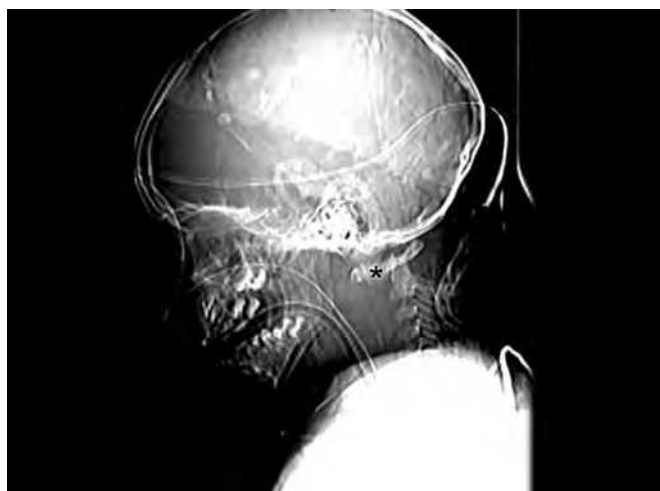


Fig. 58.4: Hyperflexion of pediatric cervical spine secondary to improper use of backboard accentuating deformity of atlanto-axial dislocation (*).

Children with AOD are typically the victims of polytrauma, and close coordination between the pediatric intensivists, general surgeons, neurosurgeons, and spine surgeons is essential. As mentioned previously, prognosis is guarded in these patients, particularly those with anoxic brain injury. Before proceeding with surgery, a realistic discussion must be had between all involved teams and the family, who will typically push for any intervention in the frequently unrealistic hope that it may cure the child.

Definitive surgical stabilization of AOD in the pediatric patient requires a fine-cut computed tomography (CT) (1 mm slices) scan of the cranial-cervical junction. In children younger than 12 months, an iliac-crest autograft onlay technique is recommended.²⁷ This consists of decorication of the occiput, as well as the C1 and the C2 lamina with wiring of strips of autogenous iliac-crest bone graft via drill holes in the cranium and sublaminar wires at C1 and C2 (Figs. 58.5A and B). A key technique to passing sublaminar wires is to use the blunt end of a 0-Vicryl on a tapered, e.g. “SH” needle (Ethicon, Somerville, NJ) to preliminarily pass a strand of suture behind the lamina. This can then be gently flossed back and forth to create a tract for the wire itself.²⁸ Because onlay wiring provides little inherent stability, these patients are kept in a halo-thoracic vest or a Minerva cast for a minimum of 3 months postoperatively, ideally until definitive fusion is seen. In children older than 12 months, rigid internal fixation of the OCC is frequently possible. Anderson et al. have published a useful algorithm for the stabilization of the



Figs. 58.5A and B: A 17-year-old male (ASIA E) with Type II odontoid fracture, preoperative lateral X-ray (A) treated with C1-2 transarticular screw fixation and sublaminar wiring (B).

craniovertebral junction in pediatric patients.²⁹ The first goal is to evaluate for the placement of C1-C2 transarticular screws to act as an anchor for either a titanium loop or an occipital plate. Some authors have shown that up to 89% of children may be candidates for C1-C2 transarticular screw placement.³⁰ Careful evaluation of the course of the vertebral artery is essential, and vertebral artery injury is known to occur in even the most experienced hands. 3.5 mm screws are recommended for patients younger than 4 years of age, and 4.0 mm screws for those older than 4.³¹ After successful placement of a C1-C2 transarticular screw, a looped titanium rod can then be secured to the screws via a set-plug and to the occiput via wires; screws, or an occipital plate, may be used in older children. Other potential anchoring sites include C2 pars screws, C2 laminar screws, and subaxial lateral mass screws.²⁹ Halo immobilization may be unnecessary in patients with rigid internal fixed AOD,²⁹ although the authors would recommend a cervical collar be continued until evidence of fusion is seen.

Fractures of the Atlas

Fractures of the atlas are relatively rare in the pediatric population.⁵ Moreover, because these fractures are generally associated with an increase in canal volume, they are rarely associated with SCI. Fractures through the synchondroses of the atlas have also been described.³² In general, these patients can be immobilized in a halo vest, as described above, while their fracture heals.

Atlanto-Axial Instability

Like, AOD, traumatic atlanto-axial instability (AAI) results from the disruption of the ligamentous stabilizers of the OCC as a result of high-energy trauma. This injury is more commonly observed in children younger than 11 years of age, most likely because of the proportionally larger size of the head in these patients.⁵ That children have greater motion at the C1–C2 articulation than adults is well recognized. Up to 4 mm of motion in the anterior atlanto-dens interval on flexion–extension radiographs is normal.³³ This increased ligamentous laxity may confound diagnosis based on plain radiographs or CT scans, although this is less of an issue with the widespread use of MRI.

Spinal cord injury following traumatic AAI should be approached in a similar manner to AOD. These children are also commonly multiply injured, intubated on scene, and may have hypoxic brain injury secondary to respiratory arrest from their high cervical SCI. Temporary halo thoracic fixation of these injuries is recommended to stabilize the spine during the initial evaluation and treatment of the patient.

Definitive surgical stabilization of traumatic AAI in pediatric patients also follows a similar algorithm to AOD. For children younger than 1 year of age, although the use of C1–C2 transarticular screws has been reported,²⁹ a critical evaluation of the course of the vertebral artery must be done prior to surgery. If there is any doubt about the feasibility of a transarticular screw, we recommend placement of onlay iliac-crest bone graft with posterior wiring of C1–C2 with postoperative halo thoracic immobilization. In children older than 1 year of age, a Brooks sublaminar technique with bone grafting is also useful. C1–C2 transarticular screws are also feasible and in one large study have a reported 100% fusion rate.³¹ However, the incidence of vertebral artery injury in this series was two of 67 (3%).

Atlanto-axial instability associated with os odontoideum is also a relative indication for C1–C2 fusion, particularly in the setting of cervical cord neurapraxia (CCN) or cervical SCI. Patients with os odontoideum may have significant instability noted on flexion–extension radiographs, up to 1.3 cm.³⁴ To prevent recurrent CCN or possibly SCI, the authors recommend C1–C2 fusion for patients presenting with CCN and os odontoideum. Transarticular screws are the fixation technique of choice and have high reported fusion rates.³¹

Odontoid Process Fractures

Fractures of the odontoid process are relatively rare in younger children; however, they become more common in children older than 12 years of age.⁵ Pediatric odontoid fractures are infrequently associated with SCI.³⁵ In young patients, the odontoid fracture can typically be reduced either with hyperextension of the neck, manipulation under anesthesia or traction, or halo thoracic immobilization or Minerva casting with very high reported rates of union.³⁵

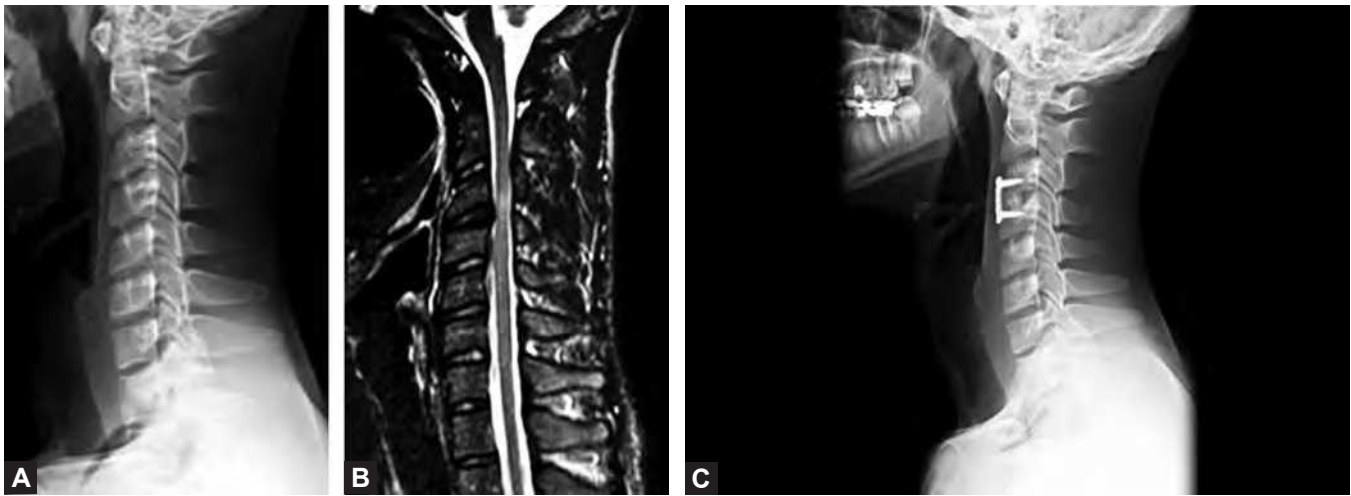
Odontoid process fractures in adolescents follow similar patterns of injury as found in adults. The vast majority of these can be treated with halo thoracic immobilization while the fracture heals. Although their study consisted primarily of adults, the findings of Koivikko et al. regarding the increased rates of nonunion following conservative management of odontoid fractures in patients with fracture gap >1 mm, posterior displacement >5 mm, and posterior redisplacement >2 mm are also illuminating in the treatment of adolescent odontoid fractures (*see* Figs. 58.5A and B).³⁶

Subaxial Cervical Spine Injuries

As mentioned previously, injuries to the subaxial cervical spine are less common, particularly in younger children. However, in children 11 years and older, there is a significant increase in the occurrence of fractures and fracture–dislocations of the subaxial cervical spine.⁵ Approximately, half of these injuries may be associated with an SCI.³⁷

Injury patterns are generally similar to those seen in adults and include compression fractures, burst fractures, facet dislocations and fracture–dislocations. Unique to the pediatric population are fractures of the physeal end plates,³⁸ which may be highly unstable, and are commonly associated with SCI.³⁷

For children with subaxial cervical spine injuries, initial treatment is guided at reducing any deformity to realign the spinal canal and relieve compression on the spinal cord. The authors recommend halo ring be placed in the operating room, as described previously, and traction applied in a gentle manner to achieve reduction. Commonly, 3 months of halo thoracic fixation may represent definitive treatment, particularly for simple facet dislocations and burst fractures. Fracture–dislocations are unstable injuries that commonly require operative treatment.



Figs. 58.6A to C: Lateral cervical spine X-ray (A) and sagittal STIR MRI (B) image demonstrating severe congenital cervical spinal stenosis and spinal cord contusion in a 17-year-old male who suffered a 15 minutes episode of cervical cord neuropraxia while playing football. Postoperative lateral X-ray after C3–4 ACDF (C).

There are multiple options for stabilization of the cervical spine in the pediatric population, including both anterior plating and posterior lateral mass screw fixation, all with high rates of arthrodesis (Figs. 58.6A to C).³⁹ Some concern exists regarding anterior fusion, which may prevent subsequent longitudinal growth of the spine in pediatric patients,³ although this has not been well studied in the literature. Successful posterior lateral mass screw fixation has been described in children as young as 6 years of age.⁴⁰ Other options for treatment include traditional onlay bone graft and spinous process or sublaminar wiring with postoperative halothoracic immobilization. The relation of timing to surgical decompression to final neurological recovery of subaxial cervical SCI has not been well studied. A recent prospective, randomized, controlled trial specifically excluded children younger than 16 years of age; however, the findings of the STASCIS trial that early decompression (<24 hours) may improve outcomes can help guide the treatment of cervical SCI in children as well.⁴¹

Thoracic, Thoracolumbar, and Lumbar Spine Injuries

Compression and burst fractures are commonly observed in children as a result of vehicular accidents, sport, and falls. The vast majority of these are not associated with SCI and may be treated with an external orthosis or cast.¹⁹ In our experience, patients presenting with 25° of kyphosis

or more, particularly when this is noted on supine CT scanning, should be watched closely for the development of progressive kyphosis.⁴² Progressive kyphosis resulting from an incompetent anterior column or a torn posterior ligamentous complex is a relative indication for surgical stabilization, which may be done via an anterior, posterior, or combined approach depending on the surgeon's preference and on the exact injury pattern. Typically, patients older than 12 years of age are treated in a manner similar to an adult.

Pediatric thoracic spinal fractures associated with SCI are a result of a high-energy injury and commonly require surgical stabilization due to their inherent instability. Physical examination may reveal a posterior step off, spinous process widening, an interspinous defect or subcutaneous ecchymosis, all of which are clues to a severe injury (Figs. 58.7A to C). Fracture-dislocations are generally reduced with hook or pedicle screw constructs. The widespread use and recognized safety of pedicle screws in adolescents and even in younger children for scoliosis⁴³ has led many practitioners to use such constructs for spinal trauma as well. Despite animal data suggesting that instrumentation across the neurocentral synchondrosis may impede the growth of the spinal canal,⁴⁴ this has not been observed clinically in children as young as 1 year of age undergoing transpedicular screw placement.⁴⁵ Furthermore, transpedicular fixation may help prevent development of crankshaft deformity following thoracic spinal fusion in a canine model.⁴⁶



Figs. 58.7A to C: A 16-year-old female status post rollover MVA with L1 burst fracture (ASIA B), sagittal CT (A) and STIR MIR (B) treated with anterior corpectomy and posterior fusion (C). Patient was ASIA E at 3-month follow-up.

The spectrum of flexion-distraction or “seat belt” injuries in children deserves special consideration (Figs. 58.8A to F). These injuries almost exclusively occur following rapid deceleration in motor vehicle accidents in children restrained by either lap or three-point harnesses. Hyperflexion of the spine occurs with the instantaneous axis of rotation located anterior to the vertebral bodies, resulting in distraction across all three columns of the spine. Flexion-distraction injuries are commonly associated with intra-abdominal injuries, particularly hollow viscus perforation, and even aortic occlusion.^{47,48} Seat belt injuries differ from true Chance fractures, which were originally described as only an osseous injury.⁴⁹

Treatment of flexion-distraction injuries is dependent on the pattern of injury. True Chance fractures may be treated in younger children, depending on their body habitus and weight, with a hyperextension cast or external orthosis. We have found it easier to place the cast or mold the brace with the patient under general anesthesia in the prone position. These ligamentous or combined osseoligamentous injuries are more easily treated with short-segment compression hook constructs or pedicle screw fixation. A fusion may or may not be included and the necessity of a formal fusion is controversial since most of these patients fuse spontaneously. In patients treated with bracing or casting, progressive kyphosis is an indication for posterior instrumentation with or without fusion. Patients with flexion-distraction injuries undergoing surgery may have less final kyphosis than those treated nonoperatively.⁵⁰

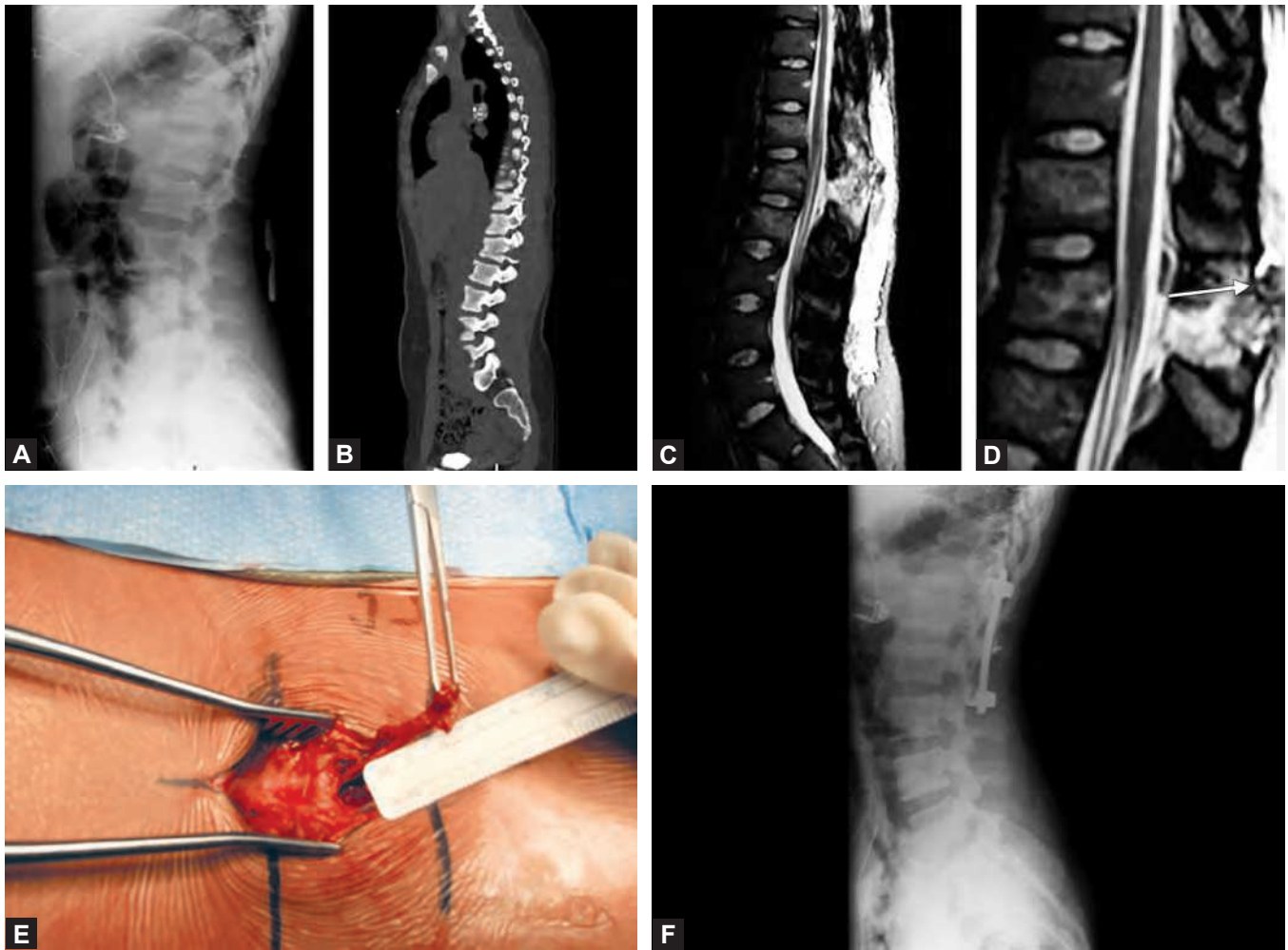
Post-traumatic Spinal Deformity

As mentioned previously, the incidence of post-SCI spinal deformity may be as high as 100% in patients who suffer injury before their adolescent growth spurt.²¹ These patients should be carefully monitored for the development of scoliosis, particularly during periods of rapid trunk growth: until age 12 in females and 14 in males (Figs. 58.9A and B).

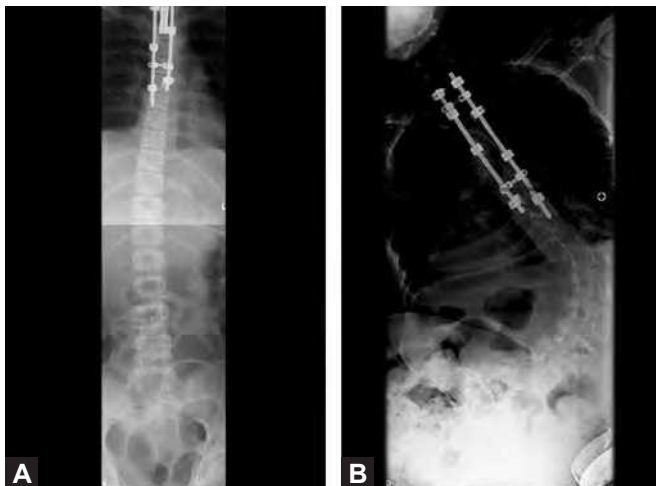
Bracing should begin immediately when any curvature is detected. Curves that are braced before they reach 10° have some hope of being successfully managed in a brace, while surgery is considered for patients presenting with curves >20°. ⁵¹ The pattern of curvature in post-SCI scoliosis is similar to that seen in neuromuscular scoliosis. The goal of treatment should be realignment of the spinal column to improve sitting balance. Fusion is almost always carried to the pelvis.

KEY POINTS

- Patterns of spinal trauma are different in children younger than 10 years of age, while older children tend to mimic fracture patterns seen in adults.
- A high index of suspicion for injuries to the occipital-cervical complex is critical in the treatment of trauma victims younger than 4 years of age, particularly those presenting with respiratory arrest and involved in motor vehicle accidents.



Figs. 58.8A to F: A 17-year-old female (ASIA E) status post 4-wheeler accident versus tree with L1 flexion distraction injuries. Lateral X-ray (A), sagittal CT scan (B), sagittal STIR MRI (C and D) images demonstrating disruption of posterior ligamentous complex, and rolling of interspinous ligament (arrow). Intraoperative photograph (E) demonstrating fascial rent and torn posterior ligamentous complex. Postoperative lateral X-ray (F).



Figs. 58.9A and B: Six months postoperative composite radiograph (A), and 6 years postoperative radiograph (B) demonstrating post-SCI scoliosis developing 6 years after complete SCI at mid-thoracic level.

- Cervical instrumentation is a useful and safe technique for treating injuries to the upper cervical spine, even in very young children older than 1 year.
- Younger children involved in motor vehicle accidents have unique flexion-distraction injuries due to seat belts and commonly present with serious intra-abdominal and vascular injuries.
- Scoliosis following spinal cord injury is common, particularly in skeletally immature patients, who should be observed until they finish growing.

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- Recent comprehensive review article summarizing available literature of pediatric spinal cord injury.

Penetrating Spinal Cord Injury

Christian P DiPaola, Thomas A St John

Snapshot

- » Pathophysiology
- » Stabbing and Miscellaneous (Nonmissile Mechanisms)
- » Patient Presentation
- » Concomitant Injuries of the Cervical Region
- » Concomitant Injuries of the Thoracic Region
- » Concomitant Injuries of the Lumbar Spine
- » Imaging
- » Special Considerations
- » Steroid Treatment
- » Operative Treatment

INTRODUCTION

Penetrating spinal cord injury (SCI) comprises a distinctive subset of spinal injury that deserves special consideration. Unfortunately, the most common reason for penetrating SCI is personal violence.¹ Gunshot wounds and stabbings account for the greatest proportion of penetrating SCI, followed by injuries from falls onto sharp objects and industrial accidents that may or may not involve projectiles or shrapnel.²⁻⁶

Penetrating SCI resulting from personal violence disproportionately affects young males between 15 and 35 years of age.⁴ In addition, industrial accidents and high energy falls also tend to affect the working (manual laborer) population. Spinal cord injury that occurs on the battlefield and in a military setting also disproportionately affects the young adult male population.⁷ Battlefield injuries inflict devastating consequences both physically and from a public health perspective.⁷ The yearly cost of care for SCI patients exceeds 100 million dollars.⁸ With only 35–40% of all SCI patients obtaining any form of paid employment, factors such as lost productivity, along with disability service care must also be considered as part of the tremendous burden and cost of these injuries.^{9,10}

Throughout this chapter, penetrating SCIs will be considered in light of the unique mechanisms that

generate them. The resultant pathophysiology, unique characteristics, injury patterns, and associated injuries will be addressed. The three main injury mechanisms (gunshot wound, stabbing, and miscellaneous) will be discussed, as each mechanism carries with it unique considerations for evaluation of the primary injury as well as associated injuries. Treatment regimens are tailored accordingly. Special considerations such as increased potential for infection and resultant treatment decisions will be identified. Patient evaluation including assessment of neurologic status, imaging, and assessment of stability, and prognosis will be taken into consideration in the context of penetrating injuries to the spine. Finally, operative and nonoperative treatments will be discussed.

PATHOPHYSIOLOGY

Gunshot Wounds

Gunshot injuries to the spine should be understood in the context of their pertinent ballistics. The energy imparted by a gunshot missile has important implications as to the tissue damage, associated injuries, and treatment decisions. The ballistics of firearms determines the energy imparted by a projectile on the injured spine and surrounding tissues. Kinetic energy (KE) is calculated

according to the equation $KE = 1/2 mv^2$ (m = mass and v = velocity). Based on this physical principle, increases in velocity impart an exponential increase in KE, which transfers into a significant increase in tissue destruction.⁴ Generally speaking, guns with muzzle velocity below 2,000 ft/s are considered “low velocity” (low energy) and over 2,000 ft/s are considered “high velocity” (high energy). There is some gray zone for interpretation between 1,000 and 3,000 ft/s.⁴ Low-velocity weapons tend to fall in the category of civilian style guns such as pistols, whereas military type assault weapons and some long-range hunting rifles are considered high velocity. Shotguns impart a low velocity but high energy due to the large mass of the pellets or slug that is delivered. Also the wounds that are generated often contain wadding, which is a packing around the shot that is considered a contaminant.⁴ Thus, shotgun wounds are considered to have high potential for infection and necessitate aggressive early debridement. Since both low- and high- velocity guns exist in both civilian and military conflicts, it is important to identify the particular weapon used in each injury, as it will help in focusing treatment.

The “mass” component of $1/2 mv^2$ imparted in gunshot wounds is important. However, tissue destruction is based on total energy delivered to the target (the injured human). This can vary substantially based on whether the bullet passes through the target or comes to a complete stop inside the target. Bullets that are jacketed tend to pass through targets, whereas bullets that yaw (wobble) enter the target at an angle that presents a greater cross-sectional area and, thus, make a larger cavity. Bullet shape and material also affect the behavior. Hollow-tipped or split-end bullets (“dum-dum rounds”) tend to expand on impact. Softer materials like lead are more likely to expand or fragment as well. All of these characteristics combine to leave a larger destructive zone of injury. Thus, more energy is imparted and greater damage is created. The shape, characteristics and material of a bullet substantially affect its flight and energy delivered. The material of a bullet (typically lead) also carries with it a potential to cause toxic effects. Nevertheless, it is rare that bullets lodged in the spine need to be removed due to lead toxicity.⁴ Serum lead levels and bone marrow biopsies can be performed to guide treatment when this is a concern. Copper has also been shown to have neurotoxic effects when adjacent to neural tissue in the spine.¹¹ However, it is not typically possible to determine bullet composition clinically. If the patient is neurologically intact, the damage of

removing fragments, when toxicity has not been demonstrated would likely not be worth the risk.

Ultimately, the tissue damage imparted by gunshot missiles can come from three mechanisms: (1) direct (missile contact) tissue destruction, (2) pressure or shockwave (concussive effect), and (3) temporary cavitation.¹² Concussive effects cause neurologic damage as missiles pass near, but not through the neural tissues. Thus, it may not be apparent based on visualized tissue destruction, but this type of injury can cause SCI. High-velocity firearms such as those used in the military are more likely to generate such effects.

Unfortunately, the initial injury sustained by the projectile is not always the final insult. Farrugia et al. reviewed the literature along with their own case presentation of reported bullet migration in the spinal canal. They concluded that bullet migration within the spinal canal is possible and may occasionally cause neurologic harm.¹³ Bullets may initially ricochet and thus do not always take a straight-line trajectory from the entrance wound. Also the gravity may influence passive migration of projectiles within the canal.

■ STABBING AND MISCELLANEOUS (NONMISSILE MECHANISMS)

Stabbing is the most common penetrating mechanism to cause SCI other than gunshots. Since other miscellaneous mechanisms are rare and their inherent characteristics are similar to stabbing with sharp objects, they will be discussed together.

A 12-year series of SCI resulting from stabbings was reported by Saeidiborjeni et al.¹⁴ Cervical and thoracic locations were involved in about 80% of injuries, split almost equally in prevalence.¹⁴ About 43% of injuries were sensory and motor complete [American Spinal Injury Association (ASIA) A].¹⁴ A stabbing or nonprojectile mechanism for penetrating SCI may also damage the spinal cord directly or indirectly. The injury may range from minor epidural involvement to complete spinal cord transection. “Indirect” injury may also result from the blunt force of the penetrating object causing contusion of the spinal cord and/or impact with the bony canal. With stabbing injuries, a “cord hemisection” type injury is more common because of the shape of the bony anatomy.¹⁵ The path of least resistance for the penetrating object (typically a knife) appears to be in the gutter between the transverse process and spinous process. The caudally and sagittally oriented



Fig. 59.1: A sharp object, which is placed adjacent to the spinous process demonstrating a typical stabbing (caudal-cephalad) trajectory. Entrance to the spinal canal is often lateralized due to the blocking effect of the spinous process over the midline and shingling of the posterior elements.



Fig. 59.2: A sharp object oriented to illustrate a more lateralized trajectory. This demonstrates how a side penetrating injury may enter the canal through the foramen and cause spinal cord injury. The extent of penetration will determine the degree of injury. One can visualize how a cord hemisection or even complete transection is possible.

spinous process provides a block to penetration across the midline (Fig. 59.1).¹⁶ Thus, the characteristic Brown-Sequard syndrome of ipsilateral motor and proprioceptive loss with contralateral pain and temperature dysfunction occurs. This scenario holds true for a posterior stabbing or fall on the back (especially to the side) that causes an impaling wound. A laterally directed penetrating object can enter the canal through the foramen, and cause nerve root and spinal cord damage (Fig. 59.2). The extent of penetration will determine the degree of neural injury. One can visualize how a cord hemisection or even complete transaction is possible. Penetrating objects can approach the spine and neural elements from 360° along the X-Y axis and at any angle from above or below the Z axis; nevertheless, the bony structures play a considerable role in limiting neural tissue damage.

PATIENT PRESENTATION

Just as with any trauma evaluation, the patient with penetrating SCI should be evaluated according to the principles outlined by Advanced Trauma Life Support. Similar to blunt trauma, an algorithmic approach to penetrating trauma based on the prioritization of airway management, breathing, and circulatory support (ABCs) is the key to optimizing survival. Penetrating injuries to the chest and abdomen are more likely to result in mortality via exsanguination or hypoxemia.¹⁷ The patient who sustains

penetrating spinal injury should be thoroughly evaluated to rule out associated or concomitant injuries. It stands to reason that adjacent structures proximal to the affected spinal anatomy should be closely evaluated. Blair et al. reviewed an 8-year series of penetrating spinal injuries in military personnel. For all comers, concomitant abdominal injuries were the most common (36%) followed by thoracic injuries (30%).⁷

CONCOMITANT INJURIES OF THE CERVICAL REGION

Penetrating injuries to the cervical spine may be more likely to have airway, visceral, and vascular injuries. The surgeon should recognize a few special considerations when evaluating patients who have sustained gunshot injuries. The majority of civilian (low velocity) gunshot wounds to the spine are stable injuries. Evaluation and treatment of life-threatening injuries should not be delayed to obtain C-spine clearance.⁴ Cervical fractures from gunshot wounds tend to be mechanically stable.^{18,19} Appropriate imaging should be obtained in order to make this determination; however, inline stabilization can be used if airway and vascular management is necessary on an immediate basis. If examination of the neck reveals pulsatile bleeding or expansile hematoma, then the carotid or vertebral artery injury should be suspected and appropriate vascular consultation should be obtained in

a timely fashion.²⁰ A high suspicion should be maintained for detecting tracheal or hypopharyngeal injury. Either may lead to early mediastinal infection.

■ CONCOMITANT INJURIES OF THE THORACIC REGION

Patients with thoracic spine injuries are more likely to have sustained pleural injuries and life-threatening vascular injuries. Auscultation of the chest is the quickest and most reliable way to rapidly assess for hemothorax or pneumothorax.⁴ Cardiac perforation or tamponade is also possible, which reinforces the need to prioritize the care of patients with penetrating spinal injuries in the same fashion as any trauma patient (“ABCs” first).

■ CONCOMITANT INJURIES OF THE LUMBAR SPINE

Patients with lumbar penetrating mechanisms have a high likelihood of associated contaminating visceral injury. These injuries have a high risk of infection and peritonitis.^{21,22} Wounds in this region must be considered to have viscus injury until proven otherwise. Also the presence of great vessel injuries must be ruled out. Typically, computed tomography (CT) scan and abdominal ultrasound are the first imaging techniques to be employed. Computed tomography angiogram or endoscopic examination can also be utilized.

Once the patient is stabilized, he or she should be evaluated for neurologic dysfunction and spinal stability. The cervical spine should be immobilized with a rigid collar until imaging is completed.⁴ The spine should be completely inspected and palpated while the patient is log-rolled. Bullet entrance and exit wounds should be identified and marked with a radiopaque marker such as a paper clip taped to the skin. Superficial debridement of clothing or surface debris and bullet fragments is recommended. But it is not necessarily recommended that wounds be deeply probed or closed. A complete neurologic examination is mandatory. Within the context of acute spinal trauma, the neurologic examination is performed in accordance with the International Standards for the Neurologic Classification of Spinal Cord Injury, formerly the ASIA standards.^{23,24} Patients who suffer SCI from a penetrating injury are much more likely to suffer complete (ASIA A) injuries.^{1,4} The authors have found it very useful to standardize communication by adopting the ASIA standardized neurologic

assessment form into chart documentation. This helps to sustain a standard of communication and reminds clinicians of all the important elements necessary for a thorough examination. This also facilitates scientific and clinical follow-up. Completeness of injury is related to the anatomic region. Patients who have sustained gunshots to the spine with incomplete injuries and patients with injuries in the thoracolumbar region have the greatest improvement in motor function. Approximately 25% of individuals are able to ambulate 1 year after injury.²⁵ Waters et al. reviewed a large series of SCIs resulting from stab wounds. Thirty-two patients were evaluated. About 63% presented with motor incomplete lesions. Half of the patients with motor incomplete lesions had asymmetrical motor patterns indicative of a Brown-Sequard syndrome. Although the percentage of patients sustaining an incomplete SCI injury following a stab injury to the spine is higher than the percentage of incomplete lesions associated with other etiologies, the amount of motor recovery when controlling for level and completeness of injury is no greater than that previously reported for other etiologies.²⁶

Hypovolemic shock should clearly be differentiated from neurogenic shock. Neurogenic shock typically occurs due to SCI rostral to T4 and upon presentation to an *emergency department* is only seen in 20% of cases.²⁷ A distinct physiologic condition exists in which the heart rate is typically <80 and the systolic blood pressure is <100. This occurs because of an overpowering of vagal output combined with a physiologic loss of sympathetic function. Once a patient is adequately volume resuscitated, neurogenic shock should be managed with pressor support. Occasionally, cardiac pacing is required.

■ IMAGING

The initial imaging of choice for patients with penetrating injuries to the spine is plain X-ray. The general location of the object (missile, blade or foreign object) and the presence, number, and location of fragments can be deduced on anteroposterior and lateral X-rays. The authors prefer marking the entry and exit wounds (in the case of projectile injury) with a radiopaque marker that is readily identifiable such as a paper clip. The use of electrocardiographic markers or other clinically common objects may be difficult to discern if they happen to be present for other purposes. By identifying the entry and exit sites, a relative path of travel can be ascertained.

Once a spinal injury is identified and the patient is physiologically stable (or if injury is suspected but cannot be fully ascertained by plain film), the CT scan should be

obtained. Plain film imaging will help guide the region of interest to target for CT scan. Thin-cut (1–3 mm) CT scan is preferred. It allows three-dimensional visualization of the missile(s) and establishes the relationship between them and the anatomic structures such as bone, disk, neural elements, and vascular structures. If vascular or visceral injury is suspected, various contrast media can aid in visualizing these structures as well. Computed tomography has the potential to cast significant artifact from metallic objects. Therefore, magnetic resonance imaging (MRI) may be a useful adjunct when anatomy is obscured.

The choice of MRI must be taken in context with the desired utility and risks. If the penetrating injury is from a bullet, it is unlikely that migration of the embedded fragments will occur and thus it is generally considered safe to perform MRI.⁴ However, if the object is composed of a highly ferromagnetic substance such as a steel wire, knife blade or nail from a nail gun, then greater caution should be exercised. The authors recommend MRI when neurologic injury is present but cannot be explained by CT imaging. Also MRI may be a helpful addition in those cases where surgical planning cannot be adequately performed with only a CT. Soft tissue and neural element visualization is obviously enhanced with MRI and, thus, can be seen as a complimentary imaging modality to CT in the case of gunshot injury. In the case of stabbings (in which the penetrating foreign object is not retained), MRI has demonstrated utility. MRI is useful in identifying the stabbing tract (high signal characteristics).²⁸ In the case of neurologic injury, there is typically a spinal cord contusion, which is demonstrated by high signal, representing intraparenchymal spinal cord edema.²⁸ MRI characteristics after stabbings can help confirm the anatomic location and correlate it with neurologic level. Furthermore, it may help to prognosticate neurologic recovery since MRI injury characteristics have been shown to correlate with prognosis after SCI.^{29,30}

SPECIAL CONSIDERATIONS

The imaging or clinical protocols for clearing the cervical spine in the case of cranial gunshot wounds are of little utility due to the relative lack of evidence.^{4,18,31,32} Gunshots to the mid-face and orbits have a much higher likelihood of cervical injury, and thus a high suspicion should be maintained.^{4,33}

When performing MRI, it should be noted that the decision to do so for penetrating injury should be made

on a case-by-case basis. The most common complaint in the case of retained bullet fragments is that the patient experiences a sense of heating in the wound, which has the potential for severe discomfort.⁴

Nonoperative Treatment

Nonoperative treatment for penetrating SCI can take the form of medical treatment and external spinal stabilization. Medical treatment is typically meant to prevent infection. The rationale for nonoperative treatment for the spinal injury is based on assessment of spinal stability, the prognosis, and the mechanism of neurologic injury.

Antibiotic Treatment

All patients with penetrating injury to the spine should be considered for tetanus prophylaxis. If there is any doubt of a patient's status, he or she should have tetanus immunization administered in the emergency department. Antibiotic prophylaxis for all penetrating spinal injuries is recommended. The choice of agent and duration is guided by the mechanism of injury and any associated internal injuries such as gastrointestinal perforation. For uncomplicated gunshots to the spine that do not involve gastrointestinal injuries, 48–72 hours of broad-spectrum antibiotic coverage is typically recommended.⁴ Penetrating SCI with associated gastrointestinal injury puts the patient at significantly higher risk of infection.³⁴

There are no randomized controlled trials or even well-designed cohort trials that have been designed specifically to answer the question of duration of antibiotic treatment in patients with penetrating SCI and gastrointestinal perforation. It is well accepted that broad-spectrum coverage should be utilized.⁴ Duration of intravenous (IV) antibiotic treatment appears to be up for some debate. Lin et al. retrospectively studied 29 patients with gunshot injuries to the spine. Of the 21 patients with a parenchymal and/or noncolonic viscous injury, 17 (77%) were treated with IV antibiotics for a minimum of 5 days. The remainder received treatment for a maximum of 48 hours. All eight patients with colonic injuries had a minimum of 5 days of antibiotic treatment. No patient developed spinal infection. The authors concluded that patients who sustained a transperitoneal low-velocity gunshot wound to their spine should be treated with a minimum of 5 days of appropriate antibiotic treatment.³⁴ Infection rates are highest with colonic perforation, especially when a projectile enters the colon before entering the spine.³⁵

Noncolonic perforations have not been shown to pose a significant risk for spinal infection (though peritonitis for small intestine and mediastinitis for esophageal injury, remain a concern).^{4,35} Roffi et al. retrospectively reviewed patients with gunshots to the spine who also sustained transcolonic, small intestine, and stomach perforations. They concluded that an extended course of broad-spectrum antibiotics (at least 7 days) combined with bedrest appeared to significantly reduce the risk of spinal or paraspinal infection.²²

Early bullet removal did not appear to be a significant factor in the prevention of infection.²² Kumar et al. came to a similar conclusion and summarized “Because the magnitude of bacterial colonization of the vertebrae after colonic injury may not be high, a nonoperative approach to treatment of abdominal viscus injuries is appropriate in patients with gunshot wounds to the spine. Broad-spectrum antibiotic coverage for at least seven days appears to be effective in preventing spinal infection, but colonic injuries are associated with an increased incidence of intra-abdominal abscess and peritonitis.”²¹

There are no studies that prove the efficacy of spinal debridement to prevent infection. In fact, the opposite appears true. In a cohort study comparing groups of surgical versus nonsurgical treatment of spine patients with transgastrointestinal gunshot wounds, a significantly higher rate of spinal infection was noted for surgically treated patients than nonsurgical patients.³⁶ There is a significantly higher rate of spinal and wound infections with transgastrointestinal gunshot wounds to the spine. Injuries that involve the colon put patients at risk for the development of spine infections after spinal surgery.³⁶ Quigley stated that randomized controlled trials are necessary for the development of a specific protocol for IV antibiotic therapy in the setting of transgastrointestinal gunshot wounds to the spine.³⁶

■ STEROID TREATMENT

Well-designed studies have been performed on patients with penetrating SCI to investigate the utility of high-dose steroids such as methylprednisolone. It has been established that steroid therapy for penetrating SCI may actually impair recovery of neurologic function.³⁷ It has also been shown that nonspinal complications such as infection and organ failure occur at a higher rate when steroids are administered.³⁸ Patients who sustain penetrating SCI

should not be treated with steroids because the efficacy of such treatment has not been proven in a controlled study.

Nonoperative Spinal Stabilization

The majority of penetrating spinal injuries are considered mechanically stable.^{4,7,12,39} Bono and Heary identify the challenges in applying historically accepted methods/classifications for spinal instability to gunshot injuries.⁴ Most stability classifications describe mechanisms of injury for blunt trauma, in which the patient is rapidly decelerating. In the case of penetrating injury, the projectile or foreign object such as a blade is traveling at a high velocity relative to the patient and rapidly decelerates. This creates a scenario whereby the penetrating object creates damage primarily in its direct path, the exception being the concussive and cavitation effects that bullets can have (which is exponentially proportional to the muzzle velocity of the projectile). Assessment of stability should be done on a case-by-case basis.

Radiographic factors such as subluxation, dislocation, acute kyphosis, and loss of key bony elements will help the clinician identify an injury that is unlikely to heal in an acceptable alignment for good mechanical function and neural protection. The concept of stability is not an “all or none” phenomenon and should be considered as a spectrum from stable, to potentially unstable, to frank instability. Likewise instability is not necessarily always identifiable with static imaging at the time of initial evaluation. Upright imaging and delayed flexion–extension X-rays (along with clinical assessment of pain) may be valuable in helping the clinician identify the “character” and “behavior” of the injury. Until these images are obtained, the patient’s injury can be braced for protection. The cervical spine is a region that needs special consideration. Unlike with blunt trauma, where radiographic criteria are relatively well accepted, any abnormal angulation or subluxation is considered suspicious for instability; thus, it has been recommended that surgeons err on the side of caution in these circumstances and treat with surgical stabilization.⁴

■ OPERATIVE TREATMENT

One of the key considerations in the evaluation and planning for surgical treatment of penetrating SCI is the determination of the goals of surgery. Surgical treatment goals include re-establishing spinal stability, obtaining neurologic decompression, wound debridement, and the

Table 59.1: Role for surgery.

Irrigation and debridement
Toxicity prevention
Removal of object/missile
Spinal stabilization
Neurologic decompression

removal of retained objects to prevent migration or toxicity (Table 59.1).

Once it has been determined that surgery is required, a key factor for consideration is the importance of timing of surgical intervention. Rapid surgical intervention is typically only warranted in patients with progressive neurologic deterioration, as documented by serial examination. This may occur by expanding hematoma or migration of retained foreign material. Shotgun and explosive wounds also mandate urgent surgical treatment mainly due to the need to debride contaminating foreign material such as wadding. Serial debridement may also be necessary to resect necrotic tissues, which often demarcates over time.

Surgical Treatment of Gunshots to the Spine

Stauffer et al.⁴⁰ retrospectively reviewed the role of neurologic decompression in patients with SCI from gunshots. They were unable to identify a benefit in terms of neurologic recovery in ASIA A (complete) SCI patients. Patients with incomplete SCI actually demonstrated a trend toward better neurologic outcome with nonsurgical decompression, though > 70% improved neurologically in both groups.⁴⁰ A high rate of complication, such as infection and fistula, has been reported with surgical decompression alone.^{4,40} Waters has prospectively studied neurologic recovery after surgical treatment. He found that surgical decompression of bullets from the spinal canal is associated with improved neurologic recovery below the T12 level. Improvement of neurologic recovery after bullet removal has not been shown in other regions of the spine. Rare instances of late neurologic decline because of retained bullet fragments have been documented.²⁵ Bono and Heary agreed that retained bullet fragments should be removed from the canal at the cauda equina level when neurologic injury is present.⁴ They also recommend removal of fragments from the canal at the cervical level, though there is limited evidence to support this. They justify the increased risk of infection and cerebrospinal

fluid (CSF) leak with the potential benefit of sparing even one cervical level, since the functional gain achieved can be significant.⁴

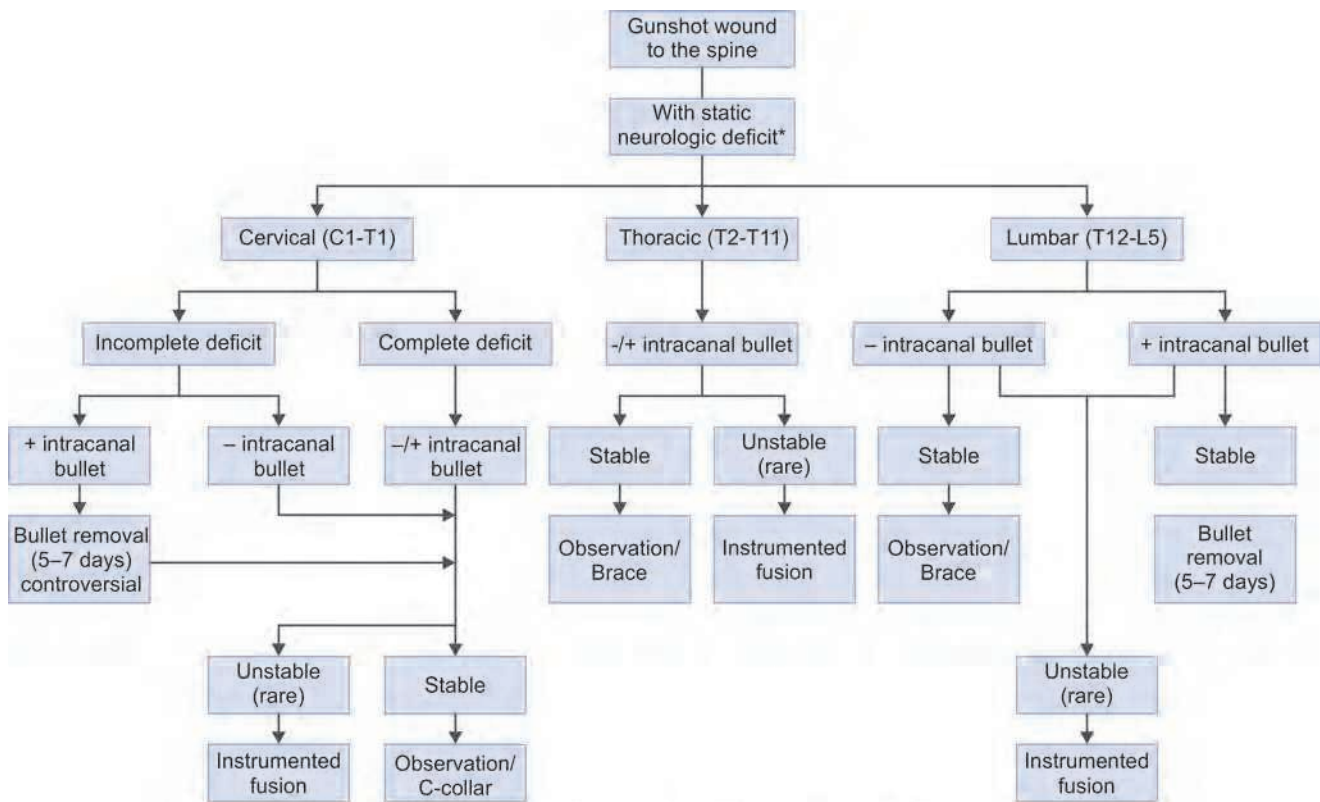
Klimo et al. and Blair et al. reviewed penetrating SCI in military populations.^{7,12} Klimo et al. found that there were serious methodological shortcomings in both the civilian and military literature groups. They, therefore, stated that decompression should be considered for any patient with an incomplete neurological injury and persistent spinal canal compromise, ideally within 24–48 hours of injury. Furthermore, they surmised that the patient should be stabilized if the spinal injury is unstable.¹²

The authors recognized the highly controversial nature of this topic and hoped that their literature review and proposed treatment recommendations would serve as a valued resource, but ultimately felt that the treating surgeon must make the final decision based on his or her opinion of the literature, his or her individual abilities and available resources.¹²

Blair et al. have performed the most up-to-date review of penetrating SCI sustained in a military population.⁷ One of the main weaknesses of the study, like so many of its kind, is that it was retrospective in nature. However, its strength is the completeness of analysis. They noted that penetrating SCI in service members is much more likely to occur from explosives.⁷ This led to blunt and penetrating mechanisms 32% of the time.⁷ Gunshots typically led to isolated penetrating spinal injuries. Blair et al. found that, overall, patients had similar results for neurologic recovery whether treated operatively or nonoperatively. This is obviously a heterogeneous group, because the gunshot and explosive penetrating injuries were not separated. Ultimately, they concluded that decompression should not be performed for complete SCI and for incomplete injuries; it should only be *considered* if clear compressive pathology exists.⁷

As far as timing is concerned regarding surgical decompression of gunshot wounds to the spine, it does not appear to make a difference whether it is performed early (<72 hours) or late, when neurologic recovery is considered, except in the case of progressive deterioration.⁴¹ Other complications such as arachnoiditis or infection may be more likely when surgery is delayed past 2 weeks, whereas CSF leak and durocutaneous fistula may be more common if surgery is done before 5 days.^{40,41} The studies that support these findings have relatively small numbers and suffer

Flowchart 59.1: The algorithm for treatment of gunshots to the spine (devised by Bono and Heary⁴) is outlined. The factors that affect decision-making include location of the spinal injury, location of the bullet, extent and chronicity of neurology, and spinal stability.



*Any progressive neurologic deficit with a radiologically identifiable cause (bullet fragments, bone fragments, compressive epidural hematoma) may warrant urgent decompression regardless of the level of the injury

from methodological flaws that make these conclusions tenuous.

In the presence of a CSF leak that is refractory to conservative management, a lumbar drain can be utilized. If the patient is at risk for developing, or has developed a durocutaneous fistula, surgery is recommended, due to the high risk of meningeal infection and failure to heal.^{22,35} Bono and Heary have devised a treatment algorithm for treating gunshots to the spine, depicted in Flowchart 59.1.

Surgical Treatment of Nonmissile Penetrating Spinal Injuries (Stabbing, etc.)

Nonmissile penetrating injuries to the spinal cord are more rare than gunshots. The information available to guide surgical treatment is loosely based on literature from gunshot data as well as relatively small case series and reports on specific injuries. In contrast to gunshot injuries, there is a greater consensus on surgical treatment of impale-

ment injuries. While it is not typically necessary to remove retained bullet fragments, it is generally recommended that retained foreign material (i.e. knife tip, wire, nail, or other fragments) be removed from the spinal canal to enhance neurologic recovery and decrease infection risk.^{14,16,42-44}

Saeidiborojeni et al. published a 12-year case series on SCIs that resulted from stabbings.¹⁴ About 43% of stab injuries resulted in complete SCI, while 57% were incomplete. There was very little chance of neurologic recovery for ASIA A lesions.¹⁴ Approximately, 70% of incomplete injuries improved.¹⁴ Unfortunately, the authors did not expound upon the role of surgical treatment. The majority of papers that dealt with surgical treatment of nonprojectile (impalement) injuries to the spinal cord were small case series or case reports. They highlighted unique scenarios that may help surgeons guide treatment when similar situations arise.

Wang et al. reported on a case of a wire-penetrating injury to the C6 spinal level.⁴⁴ The patient had a piece of bull whip snap off and impale him in his anterior neck.

The fragment pierced the dura and spinal cord and caused mild paraplegia. It was successfully removed and the CSF leak was easily plugged with bone wax. The patient had near complete neurologic recovery. Manzone et al. also lend support to the premise that removal of retained foreign objects from stabbing injuries can promote neurologic recovery.⁴⁵ They reported on a patient who had been stabbed and had the tip of the knife broken off into the spinal canal. The patient had a stable ASIA grade C neurologic injury for 7 days. After the tip was surgically removed, the patient experienced rapid and near complete neurologic recovery.⁴⁵

A penetrating injury to the cauda equina with wooden fragments has also been reported.⁴⁶ In this case, the patient had delayed neurologic deterioration. The wooden fragments in the spinal canal at the L2 and L3 levels were found on MRI after the patient developed a cauda equina syndrome. The pieces were successfully removed surgically and dural repair was performed.⁴⁶ This case also highlighted the potential for neurologic recovery after foreign body removal. In addition, it highlighted the need for dural repair, which may require patching, fibrin glue and possible lumbar drainage with prolonged recumbency.⁴⁶

KEY POINTS

- Penetrating spinal cord injuries (SCIs) are more likely to be stable compared to SCIs caused by blunt trauma.
- Ballistics and energy delivered via firearm projectiles needs to be a part of assessment in penetrating SCI. Kinetic energy (KE) = $1/2 mv^2$. Bullet velocity exponentially increases KE.
- Tissue damage imparted by gunshot missiles can come from three mechanisms: (1) direct (missile contact) tissue destruction, (2) pressure or shock-wave (concussive effect) or (3) temporary cavitation.
- Antibiotic treatment duration is controversial, but ranges from 48 hours for injuries that do not involve the gastrointestinal tract to upward of 14 days for injuries associated with colonic perforation. No study has proven the efficacy of debridement to the spine to prevent spinal infection.
- Surgical treatment goals for gunshots to the spine may include but are limited to re-establishing spinal stability, neurologic decompression, wound debridement and removal of retained objects to prevent migration or toxicity.

- While it is not typically necessary to remove retained bullet fragments, it is generally recommended that retained foreign material (i.e. knife tip, wire, nail or other fragments) be removed from the spinal canal to enhance neurologic recovery and decrease infection risk.

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Blair JA, Possley DR, Petfield JL, et al. Military penetrating spine injuries compared with blunt. *Spine J*. 2012;12:762-8.

A series of military spinal injuries were studied over 8 years. Concomitant injuries to the abdomen, chest, and head were common in blunt and penetrating spinal cord injury (SCI) patients. Blunt and penetrating injuries to the spinal column and spinal cord occur frequently in the current conflicts in Iraq and Afghanistan. Penetrating injuries result in significantly higher rates of SCI and trend toward increased rates of operative interventions and decreased neurologic improvement at follow-up.

Klimo P, Jr., Ragel BT, Rosner M, et al. Can surgery improve neurological function in penetrating spinal injury? A review of the military and civilian literature and treatment recommendations for military neurosurgeons. *Neurosurg Focus*. 2010;28:E4.

Based on the authors' military and civilian PubMed literature search, most of the evidence suggests that decompressive laminectomy does not improve neurological function in patients with penetrating SCI. However, there are serious methodological shortcomings in both literature groups. Surgical decompression should be considered in military penetrating SCI scenarios for any patient with an incomplete neurological injury and continued spinal canal compromise, ideally within 24–48 hours of injury; the patient should be stabilized concurrently if it is believed that the spinal injury is unstable. The authors recognize the highly controversial nature of this topic.

Waters RL, Sie I, Adkins RH, et al. Motor recovery following spinal cord injury caused by stab wounds: a multicenter study. *Paraplegia*. 1995;33:98-101.

A series of patients with SCI due to stab wounds was studied. Fifty percent of those with motor incomplete lesions had asymmetrical motor patterns indicative of a Brown-Sequard syndrome. Although the percentage of

patients sustaining an incomplete SCI injury following a stab injury to the spine is higher than the percentage of incomplete lesions associated with other etiologies, the amount of motor recovery when controlling for level and completeness of injury is no greater than previously reported for other etiologies.

Quigley KJ, Place HM. The role of debridement and antibiotics in gunshot wounds to the spine. *J Trauma*. 2006; 60:814-9; discussion 9-20.

Surgical treatment of the spine in patients with transgastrointestinal gunshot wounds showed a significantly higher rate of spinal infection than did nonsurgical treatment of the spine. No significant difference in spine infection rate was seen with adequate versus inadequate antibiotic coverage in the transgastrointestinal subset or in the development of wound infections with spine surgery or varying antibiotic coverage. There is a significantly higher rate of spine and wound infections with transgastrointestinal gunshot wounds to the spine. These injuries, particularly those that involve the colon, put patients at risk for the development of spine infections after spinal surgery. Randomized controlled trials are necessary to establish a specific protocol for intravenous antibiotic therapy in the setting of transgastrointestinal gunshot wounds to the spine.

Novel Approaches to Neural Repair and Regeneration after Spinal Cord Injury

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Snapshot

- » Primary Injury
- » Secondary Injury
- » Astroglial Scar
- » Interventions for Acute Spinal Cord Injury

INTRODUCTION

Spinal cord injury (SCI) is a complex and potentially devastating event that can lead to permanent disability. The process involves disruption of ascending and descending axonal pathways and an ensuing inflammatory response that results in progressive neuronal loss, axonal destruction and demyelination at the site of injury.

In developing countries, the incidence of SCI is approximately 25.5 cases per million per year.¹ Nearly 10,000 new cases of acute paralysis are documented each year, and social costs are estimated at 10 billion dollars per year in the United States alone.² The vast majority of SCI patients are male (82.8%),¹ who are most frequently between 16 and 30 years of age.³ The two leading causes of SCI are motor vehicle crashes and falls, with complete SCI more common than incomplete injuries (56.6% vs. 43.0%, respectively), and paraplegia more common than quadriplegia (58.7% vs. 40.6%, respectively).¹

PRIMARY INJURY

The pathophysiology of SCIs is multifactorial and multiphasic, including primary and secondary injury mechanisms (Fig. 60.1).⁴ The primary mechanism, as described by Walker et al., involves direct mechanical trauma to the spinal cord.⁵ Clinical outcomes vary depending on numerous factors including the impact of injury, duration

of compression, displacement of the cord, acceleration of impacting forces and the amount of kinetic energy absorbed at the time of injury.^{6,7}

After the primary offense, the propagation of damage is thought to occur through activation of biochemical events leading to cellular dysfunction and death (Fig. 60.2).⁸⁻¹⁰ Of note, the spinal cord undergoes progressive inhibition of recovery that results in additional neuronal damage.^{11,12} The secondary injury is associated with the inflammatory response,¹³ and leads to pathologic changes including hemorrhage, edema, necrosis, axonal fragmentation, demyelination and eventually cyst and scar formation (Fig. 60.3).¹⁴ These processes begin immediately following the injury and continue for weeks.

SECONDARY INJURY

Vascular Damage

The secondary injury cascade generally begins with vascular disruption, including microcirculatory insufficiency.¹² However, the definitive cause of vascular insufficiency after posttraumatic SCI remains unknown.¹⁵ Senter et al. suggested that the mechanism involves the autoregulation of spinal cord blood flow, which is damaged in acute SCI.¹⁶ These patients usually have systemic hypotension and bradycardia from neurogenic shock and decreased sympathetic tone. The loss of autoregulation after SCI results in vascular hypoperfusion due to capillary loss,

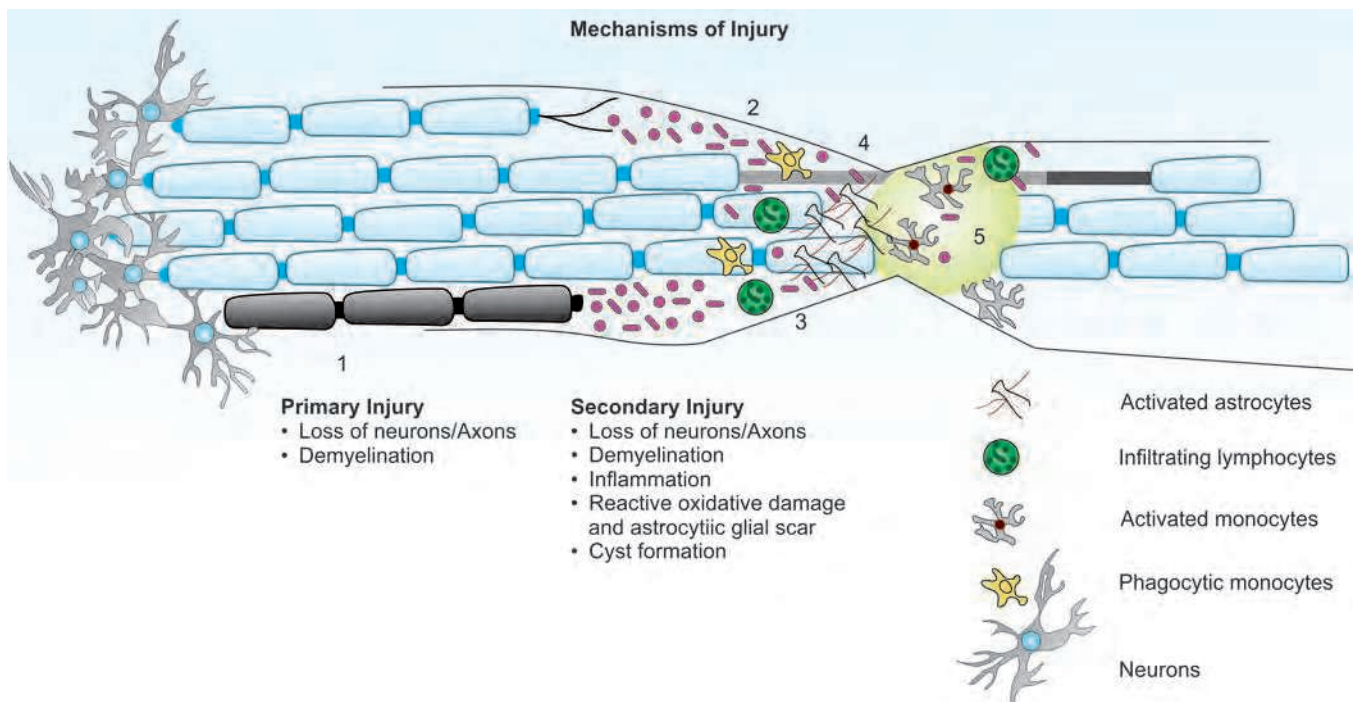


Fig. 60.1: Primary and secondary injury mechanisms.

Source: Salewski R, Emrani H, Fehlings MG. Neural stem/progenitor cells for spinal cord regeneration.

vasospasm, thrombosis, and systemic hypotension, which can lead to cellular ischemia and chromatolysis in the anterior horn cells.¹⁷

Some authors have suggested that the severity of cord injury correlates with the degree of post-SCI ischemia, and recovery of neurologic function is dependent on the improvement of blood flow.¹⁸⁻²⁰ For this reason, it has been recommended that mean arterial pressure be maintained at or above 90 mm Hg after SCI.²¹

Oxidative Stress and Lipid Peroxidation

After a temporary period of ischemia, the spinal cord undergoes unregulated reperfusion, resulting in an increase in oxygen-derived free radicals, which may exacerbate the secondary damage.^{22,23} Free radicals are produced in normal cellular processes as a part of the mitochondrial electron transport chain and the microsomal cytochrome P-450 system (Fig. 60.4).²⁴ These free radicals increase in response to brisk reperfusion following oxygen deficit, resulting in the oxidation of cellular membrane lipid fatty acids. This membrane lipid peroxidation produces more free radicals, which in turn leads to more lipid peroxidation, in a chain reaction fashion.²⁵ Free radicals contribute to other related

processes, such as modulation of membrane receptor function, denaturation of DNA and mitochondrial proteins, and inhibition of sodium-potassium ATPase, which lead to metabolic collapse and cell death.^{26,27}

Excitotoxicity

After SCI, intracellular glutamate release occurs secondary to excess free radicals, which then leads to impairment of neuronal membranes, depolarization, and cellular death. Glutamate is the most excitatory neurotransmitter in the central nervous system (CNS) and peripheral nervous system (PNS), and is important for learning and memory and helps regulate brain development.²⁸ However, glutamate must be present in the proper concentrations, and imbalance may contribute to neuronal damage after SCI.

Glutamate receptors are divided into two groups, ionotropic and metabotropic.^{29,30} The ionotropic receptors, which include N-methyl d-aspartate (NMDA), α -amino-3-hydroxy-5-methylisoxazolepropionate (AMPA) and kainate, mediate the passage of calcium and sodium ions. Metabotropic glutamate receptors activate ion channels via G proteins through secondary intracellular messengers.

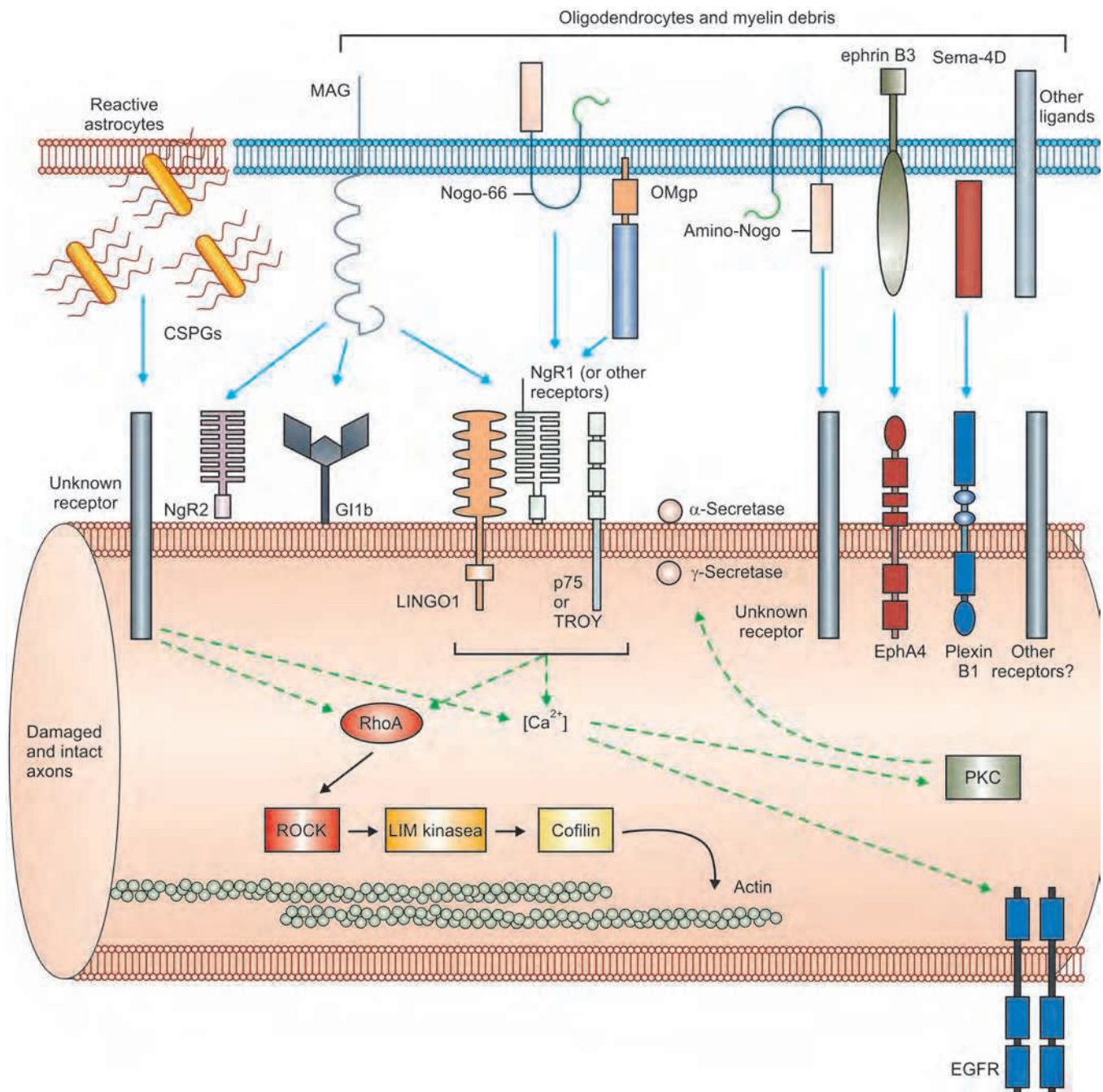


Fig. 60.2: Glial response and intracellular signaling mechanisms.

Source: Yiu G, He Z. Glial inhibition of CNS axon regeneration. *Nat Rev Neurosci.* 2006;7(8):617-27.

Excessive glutamate activates NMDA receptors, which mediates entry of extracellular calcium into the cell, and trigger the release of calcium from the cytoplasmic compartment.³¹ This increased calcium concentration activates destructive enzymes such as phospholipases and lipoxygenases, which cause cellular damage and death.³²

Immune Response

Inflammation is a part of the complex biological response after injury, and includes cellular (neutrophils, macrophages and T cells) and noncellular components (cytokines, prostaglandins and complements). The CNS is more

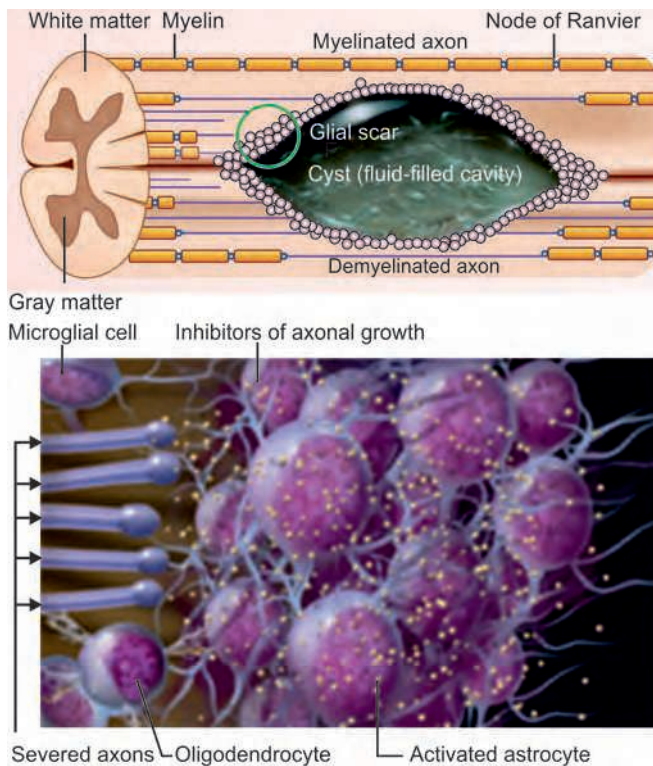


Fig. 60.3: Glial scar and cyst formation.

Source: Macaya D, Spector M. Injectable hydrogel materials for spinal cord regeneration: a review. *Biomed Mater.* 2012;7(1):012001.

susceptible than other tissues to the inflammatory and immunologic response.³³

After SCI, the site is initially infiltrated by neutrophils, which secrete lytic enzymes and cytokines that may further damage local tissue and recruit other inflammatory cells.^{34,35} Once active, neutrophils will secrete additional cytokines that stimulate the production of phospholipases and cyclooxygenase.³⁶

Prostaglandins (PGE₂, PGD₂, PGF_{2a}, and PGI₂ in particular) and thromboxanes are produced following oxidation of arachidonic acid by cyclo-oxygenase. Prostaglandins enhance the inflammatory response by altering capillary permeability, as well as activating other inflammatory cells. Thromboxanes also promote platelet aggregation and adherence.³⁷ Macrophages and local microglia produce interleukin-1 β , interleukin-6, and tumor necrosis factor α , which exaggerate the inflammatory response and tissue damage.³⁸

ASTROGLIAL SCAR

In the weeks following SCI, chronic changes occur including the development of a central necrotic region, post-traumatic

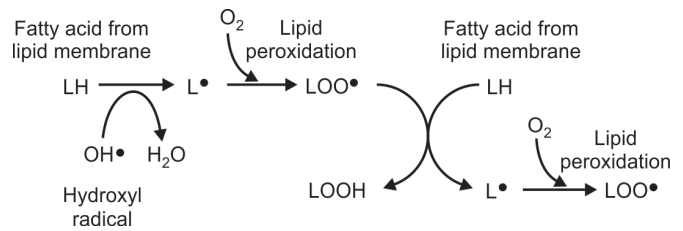


Fig. 60.4: Lipid peroxidation by free radicals.

Source: Kwon BK, et al., Pathophysiology and pharmacologic treatment of acute spinal cord injury. *Spine J.* 2004;4(4):451-64.

cysts, and, finally, an astroglial scar. The glial scar is composed of many reactive cells including astrocytes, microglia, endothelial cells, and fibroblasts.³⁹ Astrocytes play a critical role in glial scar formation (gliosis) and inhibition of axonal regeneration.⁴⁰

Gliosis is both beneficial and detrimental. On the one hand, the scar provides a biochemical protection and structural stabilization to cord integrity, thus preventing further damage. Also, the absence of gliosis is associated with impairment of the repair process of the blood-brain barrier.⁴¹ However, secretion of growth inhibitory factors by the surrounding astrocytes prevents axonal regeneration.^{42,43}

INTERVENTIONS FOR ACUTE SPINAL CORD INJURY

After traumatic SCI, a general assessment must include the confirmation and protection of the airway, breathing, and circulation. Early stabilization should be performed if the patient has an unstable fracture in order to prevent further damage.⁴⁴

Pharmacologic or biological agents used in the treatment of acute SCI act either by neuroprotection or regeneration. Neuroprotective agents prevent further inflammation and damage while regenerative strategies attempt to repair the injury site.⁴⁵

Neuroprotective Agents

Methylprednisolone

Methylprednisolone has been used after acute SCI for more than 20 years.⁴⁶ Although the precise mechanism is not completely clear, methylprednisolone may affect modulation of neuronal excitability, improve blood flow, and stabilize the injured spinal cord through inhibition of lipid peroxidation.⁴⁹ Although methylprednisolone

treatment is currently controversial, it remains an option until supplanted by future evidence-based therapies.⁴⁶⁻⁴⁸

The use and effectiveness of methylprednisolone has been assessed in clinical studies such as the National Acute Spinal Cord Injury Studies (NASCIS), a three-staged clinical trial. National Acute Spinal Cord Injury Study I was a multicenter, double-blinded, randomized trial evaluating the efficacy of low-dose (100 mg/day) and high-dose (1,000 mg/day) methylprednisolone for 10 days after acute SCI.⁵⁰ There were no differences in neurological recovery between the two groups at 6 weeks or 6 months. However, the rates of wound infection and early fatalities were higher in the high-dose group. Animal studies have suggested that the dose of methylprednisolone in NASCIS I was not effective for neuroprotection, and the dosage should be about 30 mg/kg.⁴⁹⁻⁵¹

In the NASCIS II trial, a higher dose of methylprednisolone was used, as well as the opiate receptor antagonist naloxone. In this study, 487 patients with acute SCI were randomized into three groups. The first group was treated with a bolus of 30 mg/kg of methylprednisolone, followed by an infusion of 5.4 mg/kg/h for 23 hours. The second group was treated with a bolus of naloxone (5.4 mg/kg), followed by 4.5 mg/kg/h infusion for 23 hours and the third was the placebo group. The authors concluded that treatment with methylprednisolone within 8 hours of injury improves neurological recovery after either complete or incomplete SCI. The authors also found that there was no difference in neurological recovery between the naloxone and placebo groups.⁵²⁻⁵⁴

In NASCIS III, the optimal duration of methylprednisolone treatment, as well as the efficacy of tirilazad mesylate, a lipid peroxidation inhibitor, was evaluated.¹¹ In this study, 499 patients were treated with a methylprednisolone bolus (30 mg/kg) within 8 hours and then randomized into three groups. The first group received an infusion of 5.4 mg/kg methylprednisolone for 24 hours and, in the second group, the infusion continued for 48 hours. The third group was treated with an infusion of 2.5 mg/kg of tirilazad mesylate every 6 hours for 48 hours.^{13,55} The authors concluded that if methylprednisolone treatment were initiated within 3 hours after SCI, the infusion should be maintained for 24 hours, and for 48 hours if initiated within 3–8 hours.

Gangliosides

Gangliosides are found in neuronal cell membranes, and the prototypical ganglioside GM1 (monosialotetrahexosylganglioside) is important for neuronal plasticity and

repair.^{56,57} Exogenous GM1 treatment has been associated with neuronal protection by preventing the decay of enzymes such as lactate dehydrogenase and Na⁺-K⁺-ATPase, preventing inflammation and demyelination, and inhibiting excitotoxicity.⁵⁸⁻⁶¹ While one study found improvements after treatment with GM1 after SCI at 8 weeks, this improvement was not seen at 6 months.⁶² Geisler et al. also found no difference in American Spinal Injury Association (ASIA) score in patients treated with GM1 or placebo.⁶³

Opioid Antagonists

After SCI, there is a reduction in blood pressure and perfusion of the spinal cord.⁶⁴ Opioid antagonists such as naloxone prevent pathological changes and promote motor recovery by improving spinal cord blood flow.^{65,66} Naloxone also blocks the κ -opioid receptor, which reduces inflammation.^{67,68} However, in the NASCIS II trial, patients treated with methylprednisolone along with naloxone did not show significantly greater recovery.⁵³

Thyrotropin-releasing hormone (TRH) and its analogs act as partial opioid antagonists, and improve neurologic recovery after SCI through mechanisms that remain unclear.^{69,70} White et al. suggested that TRH may facilitate transmission in somatosensory pathways, enhance sympathetic outflow from the spinal cord, and play a role in somatic motor neuron excitability.⁷¹

Glutamate Antagonists

Excitotoxicity is characterized by excessive glutamate release through NMDA and non-NMDA (AMPA/kainate) receptor activation after SCI. N-methyl D-aspartate receptor antagonists such as gacyclidine (GK-11),⁷³ dizocilpine (MK-801), and Cerestat (CNS-1102)⁷² have demonstrated significant neuroprotective effects in several studies.^{73,74}

The effects of gacyclidine include a decrease in the diameter of the ischemic lesion, and an improvement in functional recovery through prevention of excitotoxic cell death.^{75,77} Gaviria et al. suggested that the effects of gacyclidine are time and dose dependent,⁷⁶ and Hirbec et al. confirmed that optimal protection is obtained when gacyclidine is administered within 30 minutes of injury.⁷⁷

Ion Channel Blockers:

Calcium Channel Blockers

Nimodipine, a calcium channel blocker, has been examined to prevent excess calcium entry into the neuronal cell. However,

the predominant effect of nimodipine on the cord is by the way of increased blood flow through the prevention of calcium-mediated vasoconstriction.^{78,79}

Because of nimodipine causes hypotension, which can lead to hypoperfusion of the spinal cord, some authors have suggested that vasopressor therapy such as norepinephrine may be supplemented with nimodipine treatment to improve perfusion and neurologic recovery.^{80,81} Animal studies have not demonstrated significant neurologic recovery with nimodipine treatment after SCI.⁸²⁻⁸⁴

Sodium Channel Blockers

Riluzole is an Food and Drug Administration (FDA) approved sodium channel blocker used for the treatment of amyotrophic lateral sclerosis.^{85,86} Excessive activation of sodium channels is associated with cellular toxicity and neuronal degeneration. Blocking of these channels may reduce the secondary inflammatory response, and improve neurologic recovery after SCI.⁸⁷ Multiple independent studies have suggested that sodium channel blockers exhibit significant neuroprotective effects after SCI, especially in the early stages.⁸⁵⁻⁸⁹

Nonsteroidal Anti-inflammatory Drugs

After SCI, prostaglandins play important roles in the inflammatory response. Nonsteroidal anti-inflammatory drugs are generally used to relieve pain and inflammation by preventing the synthesis of prostaglandins through the inhibition of cyclo-oxygenase enzymes. Ibuprofen and indomethacin have been shown to improve axonal growth and functional recovery via suppression of the intracellular RhoA signal in an animal model.^{90,91}

Erythropoietin

Erythropoietin (EPO) is another potential therapeutic agent that stimulates the proliferation and differentiation of erythroid precursor cells. The beneficial effects of EPO are thought to be due to impending apoptosis, its inherent anti-inflammatory effects, and the restoration of vascular integrity and neuronal regeneration.⁹²⁻⁹⁵ Studies have suggested that EPO demonstrates neuroprotective and neuroregenerative effects after SCI in a rat model.^{96,97}

Minocycline

Minocycline, a second-generation tetracycline, has been shown to inhibit excitotoxicity⁹⁸ and exert neuroprotective

effects.⁹⁹ In an animal model, minocycline appeared to improve functional recovery by eliminating the destructive processes of the secondary injury.¹⁰⁰

Immunosuppressants

Cyclosporine A (immunophilin) and FK-506 (tacrolimus) are the most commonly used immunomodulatory agents that have demonstrated neuroprotective and neuroregenerative effects after SCI.¹⁰¹⁻¹⁰³ These immunosuppressants exhibit their effects through various mechanisms, principally by lowering the activity of T cells, but also through antioxidant effects, replenishing ATP stores, decreasing myeloperoxidase levels, inhibiting mitochondrial swelling, and decreasing oxidative stress.¹⁰¹⁻¹⁰⁴

Chondroitinase

Chondroitin sulfate proteoglycans (CSPGs) are potent inhibitors of axonal regeneration in the adult CNS.^{105,106} Several studies have suggested that inhibition of CSPGs using chondroitinase ABC improves functional recovery after SCI. The proposed mechanisms of action include promoting regeneration and neuroprotection of damaged axons, increasing the plasticity of uninjured pathways, and limiting scar tissue.¹⁰⁷⁻¹⁰⁹

Ethyl Pyruvate

Pyruvate, an organic acid, supplies energy to living cells through the Krebs cycle and prevents neuronal damage as a free radical scavenger for hydrogen peroxide.¹¹⁰⁻¹¹² Treatment using ethyl pyruvate has demonstrated a neuroprotective effect after SCI through inhibition of astrogliosis and neuroinflammation, as well as improved neuroregeneration via antioxidative properties in mouse and rabbit models.¹¹³⁻¹¹⁵

Atorvastatin

Atorvastatin (trade name Lipitor) is a member of the statin family used for lowering blood cholesterol by inhibiting HMG-CoA reductase. This compound also demonstrates anti-inflammatory properties.¹¹⁶ In animal models of SCI, treatment with atorvastatin has been shown to be neuroprotective by decreasing the inflammatory response of the secondary injury, and by reducing neuron and oligodendrocyte apoptosis.¹¹⁷⁻¹¹⁹

Alprostadi

Alprostadi, an analog of prostaglandin E1 (PGE1), improves motor function after SCI by increasing spinal cord blood flow,¹²⁰ reducing inflammation,¹²¹ and upregulating the expression of vascular endothelial growth factor.^{122,123} This vasoactive agent may prove to be effective in the treatment of SCI.

Neuroregenerative Strategies

Cell Transplantation

Cell-based therapies to repair damaged neuronal cells are a promising new concept for the treatment of SCI. The cell types used include bone marrow stromal cells (BMSCs), human embryonic stem cells (HESCs), olfactory ensheathing cells (OECs), and induced pluripotent stem cells (iPSCs).¹²⁴ However, there is currently no consensus on what type of stem cell or progenitor cell would be the ideal source for cellular grafts.¹²⁵ Growth factor (GF) secretion is observed after transplantation of these cells.¹²⁶ These GFs also exhibit antiapoptotic effects and improve axonal regrowth, remyelination, and neuronal plasticity.^{127,128}

Bone Marrow Stromal Cells

Bone marrow stromal cell is a unique cell that can differentiate into glial and neuron-like cells, as well as cells expressing markers of immature neurons.^{129,130} Several animal studies have suggested that BMSC transplantation after SCI can promote repair of the injured spinal cord and recovery of neurological and locomotor functions.¹³¹⁻¹³⁴ Ide et al. examined the effects of BMSCs in a rat model of subacute SCI lesion. Two weeks after SCI, cultured BMSCs derived from GFP-transgenic rats were transplanted directly into the lesion. Fourteen days after transplantation, cavity formation was reduced, and locomotor recovery was improved compared to the control group.¹³⁵

Cotransplantation of BMSCs with various cells and factors has also been studied. The addition of Schwann cells (SCs) reduces the formation of glial scar, remyelinate the injured axons, and promotes functional recovery.¹³⁶⁻¹³⁹ Cotransplantation of BMSCs with olfactory ensheathing cells,^{140,141} stimulating factors, such as granulocyte macrophage-colony stimulating factor,¹⁴² brain-derived neurotrophic factor (BDNF),¹⁴³ and other GFs¹⁴⁴ have all been shown to improve functional recovery.

Paul et al. compared delivery methods for cell transplantation using either lumbar puncture (LP) or intravenous delivery in a rat model. They concluded that both methods of cell transplantation were effective, but in LP delivery, cell engraftment and tissue sparing were significantly better, and the host immune response was reduced.¹⁴⁵

Olfactory Ensheathing Cells

Olfactory ensheathing cells are the glial cells of the olfactory system, also known as olfactory SCs. Olfactory ensheathing cells are different from the glial cells of other systems because of their developmental origin and presence in both the peripheral and CNSs. Olfactory ensheathing cells create olfactory axons from the nasal epithelium to the olfactory bulb.^{146,147} Olfactory ensheathing cells also secrete GFs that support new olfactory axons and promote axonal regeneration after SCI.¹⁴⁸ Several studies have suggested that OEC transplantation promotes neural regeneration and improves functional recovery^{141,149-151} via multiple mechanisms including promotion of tissue sparing,¹⁵² stimulation of axonal regeneration,¹⁵³ and reduction in secondary damage by modulating inflammation.¹⁵⁴

Lu et al. demonstrated that transplantation of OECs can promote axonal regeneration after SCI. In a rat model, they transected the thoracic spinal cord at the T10 level. After 4 weeks, OECs were transplanted into the spinal cord. Ten weeks later, locomotor activity of these rats was significantly improved compared with the control group.¹⁵²

Human Embryonic Stem Cells

Human embryonic stem cells are pluripotent stem cells derived from totipotent cells of the early-stage embryo.^{155,156} Many researchers have found that after SCI, treatment with HESC transplantation may have potential therapeutic effects, including improvement of functional recovery and axonal regeneration.¹⁵⁷⁻¹⁶³ These cells may prove to be a useful therapeutic strategy to repair the injured spinal cord.

Kerr et al. transplanted oligodendrocyte progenitor cells (OPCs) derived from HESCs into a contused SCI rat model at 3 and 24 hours following injury. The authors found that the cells survived for a minimum of 8 days, and migrated away from the injection site after 1 week. They also found increased neurological responses in the OPC group compared to controls.¹⁶⁴

Induced Pluripotent Stem Cells

Induced pluripotent stem cells are a type of pluripotent stem cell artificially derived from nonpluripotent cells by transducing different genes.¹⁶⁵⁻¹⁶⁷ Because IPSCs can be developed from a patient's own somatic cells, it was believed that treatment with IPSCs would elude any immunogenic response, while circumventing potential ethical dilemmas.^{168,169} However, IPSCs are associated with a potential risk of tumor formation due to inappropriate reprogramming of somatic cells and through transduction with retroviruses and lentiviruses, which activate exogenous transcription factors. The safety and effectiveness of IPSC treatment should be assessed prior to clinical use, including the differentiation potentials and tumorigenic activities.¹⁷⁰

In recent years, IPSCs have been produced without using a viral vector. Using IPSCs without inserting exogenous genes appears safe and preferable.^{171,172} Animal studies suggest that IPSC treatment using newer delivery models promotes functional recovery without tumor formation.^{169,170,173,174}

Growth Factors

Astrocytes are involved in the regulation of SCI, and are vital for neuroprotection and metabolic support.^{175,176} After SCI, astrocyte precursors surround the lesion and enhance the upregulation of epidermal growth factor receptor (EGFR), which is necessary for neuroprotection and normal glial scar formation. Transforming growth factor alpha (TGF- α) exhibits mitogenic effects that enhance astrocyte invasion and axon regeneration through activation of the EGFR. Infusion of TGF- α into the injured spinal cord enhances astrocyte infiltration and axonal growth, and may be a potential treatment strategy.^{177,178}

Brain-derived neurotrophic factor, a member of the neurotrophin family of GFs, stimulates growth and mediates the survival of existing neurons and the differentiation of new neurons.¹⁷⁹ Several studies have suggested that administration of BDNF after SCI is associated with better neurological regeneration and improved functional outcome,¹⁸⁰⁻¹⁸⁴ possibly due to this factor's ability to promote axonal regeneration, plasticity and remyelination.¹⁸⁵

Biomaterials

Biomaterials have been developed in attempts to bridge the area of injury with a bioengineered scaffold with chemical and physical properties to create a stimulatory and permissive milieu.¹⁸⁶⁻¹⁸⁸ Approaches that combine

biomaterials with drugs to carry and deliver cells to the injured cord could improve tissue repair and functional recovery.¹⁸⁹⁻¹⁹² Several studies have suggested a synergistic effect favoring neural regeneration¹⁹³ when biomaterials were combined with BMSCs,¹⁹⁴⁻¹⁹⁶ SCs¹⁹⁷ and OECs.¹⁹⁸

Macrophage Transplantation

Neuronal regeneration of the injured spinal cord is restricted because of limited immune response and insufficient macrophage recruitment.¹⁹⁹ Several studies have demonstrated that treatment with macrophage transplantation after SCI improves neuronal repair by releasing cytokines and promoting a permissive extracellular environment.²⁰⁰⁻²⁰² However, in a large-animal SCI study, autologous macrophage implantation did not improve neuronal regeneration.²⁰³

Rho Antagonists

The role of Rho, a small GTPase, which plays an important role in the intracellular signaling pathways in the axonal tip (growth cone), has been extensively studied and drug interventions targeting this pathway are in the initial phases of clinical trials.²⁰⁴ Leakage of myelin proteins and the process of gliosis after SCI lead to activation of Rho, causing neuronal apoptosis that leads to a block in neuronal attempts to regenerate.²⁰⁵ Rho antagonists, thus, have a potential neuroregenerative role in promoting axonal regeneration and sprouting. Novel anti-Rho molecules like BA-210 (Cethrin) have shown encouraging results in phase 1 and phase 2a trials and may soon find wider clinical application.²⁰⁴

Anti-Nogo Antibodies

Antibodies against the myelin-associated protein "Nogo-A" present in oligodendrocytes and their membranes have shown to result in upregulation of growth-specific proteins and enhanced regenerative and compensatory sprouting of fibers.²⁰⁶ Phase 1 clinical trials applying anti-Nogo A antibodies have been promising and currently phase 2 trials are on the way.²⁰⁶

CONCLUSION

Spinal cord injury is a potentially devastating traumatic event resulting in death of neuronal cells, degeneration of axons, gliosis, and functional deficit. There is currently no curative treatment for SCI.

Because the pathophysiology of SCI is multiphasic and multifactorial, an effective treatment will likely require a combination of therapeutic approaches that promote neuroprotection to prevent further damage, minimize the inflammatory response and stimulate regeneration. Neuroregenerative treatment strategies facilitate repair of the damaged neuronal tissues and include cell transplantation, allograft treatment, GFs, macrophage transplantation, and biomaterial engineering. Recent studies have demonstrated that cell transplantation strategies hold promise in improving neural cell regeneration and functional recovery after SCI.

KEY POINTS

- Gliosis contributes to inhibition of axonal regeneration, as well as biochemical protection and structural stabilization.
- Neuronal regeneration after SCI is limited.
- Reducing inflammation and astroglial scar is a key target for treatment.
- Combination treatment strategies could be effective.

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Nutrition in Spinal Cord Injury

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Snapshot

- » Introduction to Nutritional Requirements and Energy Expenditure
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INTRODUCTION

The spinal cord injury patient often presents with a complex set of injuries requiring the cooperation of multiple medical services as well as management of multiple physiologic systems in order to generate optimal treatment results. These patients may have suffered polytrauma involving musculoskeletal damage, as well as neurologic or visceral injuries. They may be subject to prolonged periods of intubation, multiple procedures (either tests or surgical), and prolonged periods of bed rest. Their bodies are subject to the initial injury, surgical procedures, prolonged periods of time without oral intake, and risk of infection, which are all ultimately extremely taxing. In order for the body to withstand this process, heal, and fight off infection, elevated energy expenditure is required; and, therefore, optimal nutrition is a key component to patient care. At this juncture, strict nutritional recommendations based on spinal cord injury specific research are not yet clearly delineated.

However, based on current knowledge of the physiologic response to injury, the metabolic and hormonal environment of the critically ill or injured patient, postoperative requirements of the spine surgery patient, and current trends in nutritional management of these individuals, general management guidelines can be extrapolated.

Regarding spinal cord injury patients specifically, the acute phase of injury and treatment can be extremely threatening; however, the condition of the patient after stabilization, may require long-term observation, management, and preparation in order to avoid complications which can develop as a result of the patient's new chronic condition. Nutritional management becomes an important component of the overall care of these patients in order to promote a favorable biochemical environment for healing, prevention of infection and tissue compromise, as well as surgical optimization.

INTRODUCTION TO NUTRITIONAL REQUIREMENTS AND ENERGY EXPENDITURE

Energy is expended by the human body in three forms: resting energy expenditure, the thermic effect of food, and energy expended in physical activity. Resting energy expenditure generally constitutes the largest portion (approximately 60–75%) of the total energy expenditure.¹ The thermic effect of food typically represents roughly ten percent of daily total energy expenditure. Energy expended in physical activity is, therefore, the most variable. Resting energy expenditure is the energy utilized during the

activities necessary to maintain homeostasis including, circulation, respiration, cellular metabolism, maintenance of function of the central nervous system and core body temperature.

Regarding commonly utilized terminology, basal energy expenditure differs from resting energy expenditure and simply refers to “the minimal amount of energy expended that is compatible with life.”¹ Basal metabolic rate measurements are specific regarding the circumstances under which they are taken. These measurements are performed early in the morning, prior to physical activity and ten to twelve hours after the ingestion of food, fluids, or stimulants such as caffeine or nicotine. This calculation often represents 60–70% of daily total energy expenditure. If these specific are not met at the time of measurement, the calculation is then referred to as resting metabolic rate, which, in most cases, is higher.

Many factors have the potential to influence resting energy expenditure including body size, body composition, age, sex, and hormonal factors. In general, larger people have higher metabolic rates than smaller people. If two people are the same weight, the taller of the two will have the higher metabolic rate due to larger surface area. The major single determinant of resting energy expenditure is fat free mass or lean body mass. Based on this trend, athletes with increased muscle mass will tend to have a roughly five percent higher resting energy expenditure than a non-athlete. Age is related to fat free mass. As a result, the aging process may produce a resting energy expenditure which decreases at an average of two to three percent per decade of life after early adulthood. Differences based on sex are generally the result of differences in body composition and lean body mass. Metabolic rate can also be affected by hormonal status, particularly thyroid disorders (hyper versus hypo). Fevers as well as extremes in ambient temperature can affect energy expenditure. Regarding the febrile state, this rate may increase at an average of seven percent per degree Fahrenheit increase above 98.6 (13% for each degree Celsius above 37).

The standard unit of measuring nutritional energy is the calorie. This unit is defined as the amount of heat required to raise the temperature of one mL of water at 15°C by one degree. There are a variety of methods by which human energy expenditure can be measured, some more practical than others in the clinical setting. Indirect calorimetry estimates energy expenditure by measuring oxygen consumption and carbon dioxide production of the body over a given period. “The equipment varies, but

the person usually breathes into a mouthpiece or ventilated hood through which his or her expired gases are collected.”¹ Moles of CO₂ expired are divided by Moles of O₂ inspired to calculate the respiratory quotient. This number is converted to kilocalories of heat produced per square meter of body surface per hour, which is then, in turn, extrapolated to 24 hours. The respiratory quotient (RQ) is specific to the fuel mixture being metabolized. For example, The RQ for carbohydrates is 1, because the number of carbon dioxide molecules produced is equal to the number of oxygen molecules consumed (RQ = 1 for carbohydrate, 0.85 for a mixed diet, 0.82 for protein, and 0.7 for fat). Equations have also been developed to estimate basal and resting metabolic rates. The Harris-Benedict formulas, first developed in 1919, are some of the most widely used in the United States but have been found to overestimate by 7% to 24%. New equations have also been formulated in order to correct for this overestimation. New predictive equations, incorporate individual factors in order to arrive at a more specific calculation. These factors include life-stage grouping, age, weight, height, gender, and level of physical activity. These factors are incorporated in order to calculate the estimated energy requirement. Energy required to perform functions above this baseline, including growth in children, lactation in women, or healing in patients requires an additional calculation to factor for energy required for deposition of tissue.

Original Harris-Benedict equations:

Men	$BMR = 66.4730 + (13.7516 \times \text{weight in kg}) + (5.0033 \times \text{height in cm}) - (6.7550 \times \text{age in years})$
Women	$BMR = 655.0955 + (9.5634 \times \text{weight in kg}) + (1.8496 \times \text{height in cm}) - (4.6756 \times \text{age in years})$

The Harris-Benedict equations revised by Roza and Shizgal in 1984:

Men	$BMR = 88.362 + (13.397 \times \text{weight in kg}) + (4.799 \times \text{height in cm}) - (5.677 \times \text{age in years})$
Women	$BMR = 447.593 + (9.247 \times \text{weight in kg}) + (3.098 \times \text{height in cm}) - (4.330 \times \text{age in years})$

■ PRINCIPLES OF NUTRITIONAL SUPPORT FOR THE ILL OR INJURED PATIENT

Response to stress, whether the source be illness, trauma, or surgery, may lead to shock or other severe outcomes. This response is mediated through metabolic and hormonal pathways, characterized by increased catabolism, negative

nitrogen balance, and muscle wasting. There are two phases to this response as described by Cuthbertson in 1979. The ebb phase occurs immediately following injury and is associated with hypovolemia, shock, and tissue hypoxia with decreased cardiac output, oxygen consumption and body temperature. Insulin decreases, glucagon increases, and hepatic glucose production is augmented. The flow phase, which follows fluid resuscitation and restoration of oxygen transport to tissues is characterized by increased cardiac output, oxygen consumption, body temperature, and total protein catabolism. Glucose production increases as do circulating levels of glucagon, cortisol, catecholamines, insulin, and free fatty acids. Severity of injury, previous state of health, and age all seem to be associated with variability of this response.

Severe physical stress results in marked hyperglycemia, mobilization of acute phase proteins, and increased lipolysis. Branched chain amino acids are mobilized from skeletal protein to be utilized as a source of energy, while increased lipolysis leads to production of free fatty acids which are then metabolized to produce ketones (for energy production in non-glucose-dependent tissues or to resynthesize triglycerides). Potassium, phosphorous, and magnesium are all lost through urinary excretion as a result of increased protein metabolism. Epinephrine, aldosterone, and vasopressin are all increased in response to stress. Gluconeogenesis increases as does sodium and water retention to support circulating blood volume. Tissue damage and inflammation lead to production of cytokines including IL-1,6, and TNF. These metabolically active cytokines also induce gluconeogenesis and amino acid breakdown. IL-1 plays a particular role in regulating the acute phase response to stress characterized by fever, leukocytosis, skeletal muscle breakdown, and decreased serum iron and zinc.²

Regarding the management of the severely traumatized patient, one of the most severe complications can be SIRS (systemic inflammatory response syndrome). [This syndrome can be produced by a variety of stimuli including infection, ischemia, burns, pancreatitis, hemorrhagic shock and immunologically mediated organ injury.³] SIRS is diagnosed according to a strict set of criteria including body temperature above 38°C or less than 36°C, heart rate more than 90 beats/min, respiratory rate greater than 20 breaths/min, PaCO₂ less than 32 mm Hg, WBC count above 12,000/mm³ or less than 4,000/mm³, and bandemia (more than 10% immature neutrophils in the absence of chemotherapy induced neutropenia and leukopenia. Multiple

organ dysfunction can result. One particular hypothesis regarding the generation of this clinical scenario relates to gut health and the importance of enteral nutrition. This gut hypothesis indicates that disruption of the gut barrier function due to trauma corresponds with translocation of enteric bacteria into mesentery lymph nodes, liver and other organs. Enteral nutrition may act to alter antigen exposure, modulate splanchnic immune response, enhance mucosal protection, and enhance oxygen delivery to the mucosa as a result of increased vascular flow. Decreased enteral feeding can lead to villous atrophy, decreased intestinal absorption, and blunted immunity at mucosal surfaces in the gut and other regions of the body—including the lungs, due to migration of cells produced in gut associated lymphoid tissue.⁴

Energy expenditure, and therefore, nutritional requirements can be estimated for the critically ill or injured patient by methods discussed earlier which include Harris Benedict equations (incorporating age, height, weight, and stress factor (of 1.3), Indirect calorimetry, or pulmonary artery catheterization). A general estimate of 25–35 kcal/kg/day is sometimes utilized as well. Indirect calorimetry can be confounded in the critically ill patient by high oxygen requirements secondary to acidosis, a chest tube and the use of supplemental oxygen. Calculated requirements can produce overestimations secondary to paralysis necessary for intubation by as much as 30%. Data can be obtained from a pulmonary artery catheter (often placed in order to tightly monitor and manage cardiopulmonary function in the critical patient) regarding oxygen consumption based on the arteriovenous oxygen difference. The cardiovascular Fick equation can then be applied to this data to calculate cardiac output, which, in turn can be used to extrapolate energy expenditure by incorporating the known caloric value of oxygen.

Fick equation application as explained by Liggett et al. (CHEST, April, 1987):⁵

$$VO_2 = CO(CaO_2 - CvO_2) \times 10$$

where CaO₂ and CvO₂ are the oxygen contents of arterial and mixed venous blood in volumes percent, CO is cardiac output in liters per minute and VO₂ in milliliters per minute. Using 1.36 mL/g as the oxygen-combining capacity for hemoglobin, ignoring the contribution of dissolved oxygen, the following equation is obtained:

$$VO_2 = CO \times 13.6 \text{ Hgb} (SaO_2 - SvO_2)$$

The caloric value of oxygen ranges from 4.69 kcal/L to 5.05 kcal/L as the nonprotein RQ (respiratory quotient) varies within the physiologic range from 0.7 to 1.0, respec-

tively. Liggett chose a fixed nonprotein RQ of 0.85, which has a caloric value of 4.86 kcal/L. Energy expenditure in kilocalories per day (with 1440 min/day) is therefore expressed:

$$\text{REE} = \text{VO}_2 (4.86 \times 10^{-3}) \times 1440$$

Substituting equation 2 into equation 3 and combining all fixed constants, the following equation is obtained:

$$\text{Resting energy expenditure} = \text{CO} \times \text{Hgb} (\text{SaO}_2 - \text{SvO}_2) \times 95.18$$

The REE is expressed in kilocalories per day, CO in liters per minute, Hgb in grams per deciliter, and SaO_2 and SvO_2 in fractions.

Based on calculation of energy expenditure, nutritional support can be administered with an appropriate breakdown of macronutrients, including carbohydrates, proteins, and fats. Protein requirements are significantly higher in the traumatized patient, averaging 2 g/kg/day of body-weight according to ASPEN (American Society for Parenteral and Enteral Nutrition) Board of Directors guidelines (2002). The unstressed adult patient requires an average of 8 g/kg/day. There are no specific guidelines for administration of micronutrients including vitamins and mineral. Electrolytes should be closely monitored and replenished as needed. It should be noted, however, that catabolism may lead to loss of potassium, magnesium, zinc, and phosphorus and an increased need for B vitamins.

NUTRITIONAL SUPPORT STRATEGIES IN TRAUMA PATIENTS

Malnutrition is associated with impaired immune function and subsequent increased risk of infections in trauma patients.⁶ Oral feeding is always the preferred route if possible. If this is not possible due to the patient's specific clinical issues, other routes of enteral feeding should be considered as should parenteral supplementation, if energy requirements are not met by enteral feeding alone. Enteral feeding may require direct access to the gastrointestinal tract through a nasogastric, duodenal, or jejunal feeding tube. Placement of such a tube may play a role in patient care if extended periods of inability for oral feeding are expected. Difficulties of enteral feeding may result from gastric dysmotility due to intestinal insult and neuromuscular paralysis which decrease the likelihood of movement of food through the GI tract. These patients may also require TPN. Early enteral feeding has proved beneficial; yet, it should not be initiated until hemodynamic stability is achieved. Feeding the gut during periods of intestinal

hypoperfusion can increase the risk of intestinal ischemia and necrosis.

Multiple studies have been performed attempting to draw conclusions regarding the roles of specific feeding methods including enteral and parenteral methods. Many, in fact, directly compare TPN to enteral nutrition administration, and range from animal models to clinical studies. Border and associates retrospectively examined the effect of enteral feeding on the ICU treatment course of 66 blunt trauma patients. Enteral protein intake was associated with a reduction in septic severity even though the patients nourished parenterally received twice the amount of protein than the enteral fed group. Kudsk and associates randomized 98 patients into groups receiving either enteral or parenteral nutrition. These patients included those who suffered major blunt abdominal trauma, or penetrating trauma. There were no significant differences in nitrogen balance between the two groups. However, a significantly lower incidence of pneumonia, intra-abdominal abscesses, and catheter sepsis was observed regarding the enteral nutrition group. Incidence of infectious complication was measured as six to seven times greater in the patients receiving TPN. For patients suffering injuries of greater severity, the rate was at times eleven times higher. This same study also demonstrated that enteral feeding produced a greater amount of constitutive proteins and greater decreases of acute phase proteins.⁷ Generally, enteral nutrition seems to have a greater effect on aiding in prevention of infection in the critically ill patient than parenteral routes when used individually. This, however, does not discount the role of parenteral nutrition completely.

In fact, enteral feeding can lead to specific complications and difficulties not observed in patients receiving parenteral nutrition. In their study, Engel et al. recognized that, based on indirect calorimetry measurements, critical patients received on average 71% of their energy expenditure via enteral feeding. On 46% of days, patients received less than 80% of their daily energy expenditure. Factors associated with hypocaloric feeding were recognized in this study and included blunt abdominal trauma, pelvic and lumbar spine trauma, gastrointestinal intolerance, problems with the feeding tube, surgical interventions, and use of fentanyl. Based on this study, it appears that in many clinical scenarios, enteral feeding alone seems insufficient to cover the energy demands of a critically ill or injured patient in a surgical ICU. A relevant reason delineated by this study, which applies directly to the spinal trauma or cord injury patient, is that spinal trauma is positively cor-

related with a higher likelihood of the development of problems with enteral delivery of nutrients. Based on these conclusions, questions may be raised on how to bridge the gap in energy requirement and nutrition administered. If such issues in delivery of adequate nutrition enterally are common, perhaps there is a role for total parenteral nutrition as a supplement to other routes of feeding. The answer to this question has not been clarified and further research on this topic may help to better understand the potential for an interplay between both feeding modalities.

Nutritional supplementation is controversial in the setting of critically ill patients. Certain enteral formulas have been developed specifically for the traumatized or critically ill patient. These formulas typically incorporate a higher protein content as well as a higher portion of branched chain amino acids with the addition of glutamine and arginine. Regarding TPN, glutamine supplementation of these formulas may partially reverse mucosal atrophy, limit the reduction of intestinal immunoglobulin A and improve upper respiratory immunity (in mice). There is promising laboratory data on the effects of glutamate supplementation on nutritional support in mice,⁸ and should be considered in this patient population.

Investigations regarding hormonal supplementation in the trauma patient do exist and seem to be conflicting. Growth hormone administration has been researched and has been shown to improve protein and fat metabolism, with improved nitrogen balance in the trauma patient with low growth hormone levels.⁹ In 1994, two large, randomized, placebo-controlled European multicenter studies detailed the effects of growth hormone treatment in critically ill intensive care patients. Major increases in mortality and morbidity were associated with growth hormone treatment. The mechanism(s) accounting for the increased mortality remain poorly understood. These negative findings have led to a decrease in the clinical use of growth hormone and research activity regarding the area of anabolic treatment for human illness.¹⁰

NUTRITION IN THE ACUTE SETTING AND THE INTERPLAY BETWEEN ENTERAL AND PARENTERAL NUTRITION

Klein et al.¹¹ took a broad perspective regarding the analysis of nutrition with regards to the spine surgical patient. In their three-part study, three different groups of patients were analyzed. In part I, 27 patients (14 men and 13 women

with a mean age of 54 years) undergoing intervention for treatment of vertebral osteomyelitis were evaluated. Fourteen patients with either a total lymphocyte count less than 1500/mm³ or serum albumin less than 3.5 were considered malnourished. Additional data collected included age, pathologic diagnosis, past medical history, American Society of Anesthesiologists (ASA) score, length of surgery, and estimated blood loss. Outcome variables included postoperative complications and length of hospitalization. Regarding part I, postoperative complications were statistically significant as related to findings of preoperative malnourishment. The cohort for part II was comprised of 20 patients (17 men and three women, mean age of 35 years) undergoing surgery for treatment of spinal cord injury. The follow-up period averaged three years although, as in part I, the 'critical' data were from the perioperative period according to authors. Patients were divided into two groups based on postoperative nutritional status, while additional data included age, sex, type and level of injury, past medical history, ASA score, use of high-dose steroid protocol, length of surgery and estimated blood loss. Outcome variables included postoperative complications, need for prolonged intubation (>24 hours), and length of hospitalization. Data on the spinal cord injury patients indicated that 75% of the patients (15 of the 20 included) became malnourished in the postoperative period based on measurements of serum albumin and total lymphocyte count. 17 complications were noted in this part of the study, all found in the malnourished group. [These complications included pneumonia and atelectasis (nine), occipital decubiti (two), urinary tract infection (two), coagulopathy (one), infectious gastroenteritis (one), sepsis (one), and deep venous thrombosis (one).]¹¹ Although researchers found a statistically significant relationship between nutritional status and prolonged intubation, no other perioperative factors were significantly related to postoperative complications. In both groups (patients treated for infections and patients treated for injury), the postoperative complications were seen almost exclusively in the malnourished patients.¹¹ In part III, the researchers intended to address a broader patient population by evaluating data collected for 114 patients who underwent elective lumbar decompression and fusion. Likewise, the majority of complications found in part III of this study were noted to take place in patients deemed to be clinically malnourished. Prospective data collected over a three-year period (with attention to that collected during the perioperative period) was reviewed retrospec-

tively. Regarding these elective cases, 25% of these patients were found to be clinically malnourished at the time of surgery. This value increased to 42% for patients over the age of 60. Regarding data pertaining to part III, it can be argued that the overall rate of clinical malnutrition, even in patients undergoing elective surgery, is significantly higher than anticipated and offers evidence to evaluate these values preoperatively to avoid increased hospital stay, complication rates, lengthy management, and increased cost postoperatively. This study focuses attention on the importance of sound nutrition in the spine surgery patient and raises questions on how to best optimize nutritional status preoperatively and postoperatively.

NUTRITIONAL SUPPORT AND THE SPINE SURGERY PATIENT

Additional information regarding spine specific surgical intervention and nutrition can be extrapolated from nutritional studies incorporating spinal deformity patients. In 1997, Hu et al. published their data collected from a cohort of 35 patients. These adult patients underwent staged spinal reconstructive surgery and were randomized to whether they received total parenteral nutrition postoperatively. Nutritional parameters included skin fold measurements, albumin, prealbumin, transferrin, and total lymphocyte count. Values for each were collected preoperatively and at regular intervals over the course of this prospective study. Patients assigned to the TPN group began to receive it on postoperative day #1 at 40 mL/hr, which was increased until nutritional requirements were met according to calculations. Patients not assigned to receive TPN received a postoperative course of intravenous fluids until tolerating a PO diet. Hu et al. found a greater incidence of infectious complications including pneumonia and urinary tract infections in patients who had depleted albumin and prealbumin levels versus that of patients with normal levels and a longer average hospital stay. No patients in this study had complications secondary to the administration of total parenteral nutrition.¹²

In their study, Lapp et al. randomized 46 patients to receive or not receive total parenteral nutrition after surgery for spinal deformity. Researchers measured nutritional parameters including albumin, prealbumin, transferrin, total protein, and absolute lymphocyte count before surgery and at regular intervals postoperatively until at least four of the five parameters were within ten percent of their preoperative baseline values. Based on the fact that surgical techniques are similar for treatment of complex trauma

as well as deformity, the data collected during this study may possibly be extrapolated to apply to the spinal cord injury based on the nature of physiologic insult whether it is caused by surgical intervention, a traumatic event or both. Patients receiving TPN postoperatively began to receive it postoperatively on the same day of surgery. These patients were compared to patients receiving intravenous fluids until they tolerated adequate oral fluids. Their results indicated that patients receiving TPN returned to their baseline regarding nutritional parameters faster than those not receiving TPN. In this study, there was no clinical difference between these two groups regarding major or minor complications. However, perioperative nutritional depletion has been shown to increase the chance of patient morbidity and nutrition related complications.¹³ Although no significant difference in complications were observed in this study, it does suggest a potential for the role of TPN in surgical spine patients at increased risk of nutritional depletion due to preoperative health status and surgical plan. At this time more research is likely necessary to clarify the role of TPN as it relates to the management of a spinal cord injury.

NUTRITIONAL MANAGEMENT OF THE CHRONIC SPINAL CORD INJURY PATIENT

The vast majority of spinal cord injury patients survive the acute course of their management post injury. However, depending on the level of neurologic injury, their lives may be drastically changed. Decreased neurologic function may result in decreased lean body mass secondary to muscular atrophy and a decreased activity level. Related to this difference in function and lifestyle, a common secondary complication of spinal cord injury is obesity. Obesity is the direct result of positive energy balance (more calories are taken in over the course of the day than are expended). As discussed earlier, total daily energy expenditure is comprised of three elements which have each been evaluated to varying degrees through research focused on the spinal cord injury patient.

As discussed earlier in this chapter and supported by Bucholz et al. in their 2004 study, the most quantitatively significant component of total daily energy expenditure is resting metabolic rate, accounting for approximately 65% of the total.¹⁴ If corrected for lean body mass, resting metabolic rate does not seem to differ drastically between the SCI patient and an able-bodied counterpart. However,

commonly used predictive equations of resting metabolic rate based on body mass tend to overestimate requirements for SCI patients by a range of 5–32% according to Bucholz et al. 2003.¹⁵ Based on current research it is estimated that the measured resting metabolic rate of the SCI patient tends to be 14–27% lower than that of an uninjured individual. This discrepancy seems to be predominantly the result of decreased lean body mass in the SCI patient since preliminary evidence suggests that neither the metabolic activity of the fat-free body nor the obligatory phase of the thermic effect of food is different (the influence of the facultative phase of the thermic effect of food has not been elucidated). Possible derangement in sympathetic activity depending on the level of neurologic injury may also play a role, although less significant than that of fat-free mass. Catecholamines have been found to also play a significant role in energy expenditure of the able-bodied individual. High level SCI is associated with markedly decreased sympathetic discharge. Studies by Jeon et al. and Bucholz et al. help to elucidate the interplay between resting metabolic rate and the sympathetic nervous system. Jeon and colleagues compared resting metabolic rate of seven men with complete tetraplegia with that of seven able-bodied control men and found the measured resting metabolic rate to be on average 27% lower in the SCI group. The authors incorporated plasma catecholamine and plasma leptin measurements into their study. They noted that plasma catecholamine concentrations (epinephrine and norepinephrine) were at least 300% lower in the SCI patients than the controls; and, plasma leptin levels were on average 207% higher in the SCI patients. The authors concluded that the lack of direct correlation in leptin level and resting metabolic rate in the SCI patients was possibly “due to the decentralization and impairment of the sympathetic nervous system, which may interrupt the pathway of leptin-mediated energy expenditure.”¹⁶ Along similar lines, Bucholz and colleagues produced a study comparing a cohort of paraplegic SCI patients with a cohort of able-bodied controls. Like Jeon’s study, the difference in resting metabolic rate was found to be quite low (less than 2%) when corrected for lean body mass. However, Bucholz did not find a difference in sympathetic nervous system activity via measurements of urinary metanephrine. “This may have been due to the fact that (their) subjects had paraplegia, whereas those of Jeon et al. had tetraplegia.... Thus, preliminary evidence indicates that the low RMR observed in paraplegia and tetraplegia appears to be due to reduced fat-free mass, and in tetraplegia, also to reduced sympathetic nervous system activity.”¹⁴

The second component to daily energy expenditure, previously discussed, is the thermic effect of food. A limited number of research studies have evaluated for a difference in this thermic effect between SCI patients and able-bodied controls. Although the first of the studies performed by Monroe and colleagues (*American Clinical Journal of Nutrition* 1998) indicated that the thermal effect of food was 26% lower in the SCI patient group, additional studies have shown no difference.¹⁷ Aksnes and colleagues as well as Bucholz and colleagues performed similar studies to further evaluate for difference. Of note, there were differences in design among these three studies. Monroe and colleagues followed their patients and controls over a 24 hour period in a respiratory chamber; and, subjects were provided a weight-maintenance diet. Aksnes and Bucholz administered a liquid meal and then measured the thermic effect of food for two hours post-prandially.¹⁸ Bucholz does take note that it is possible that differences may have become apparent had the study been extended beyond the two hour period. Regardless, the three studies provide data that support the idea that the early or obligatory phase of the thermic effect of food between individuals with and without spinal cord injury is not significantly different. Measuring the thermal effect of food presents difficulty because “the thermic effect of food is the least reproducible component of total daily energy expenditure because it is sensitive to physiologic factors, duration of measurement, and characteristics of the test meal.”¹⁹

Physical activity accounts for approximately 25–30% of total daily energy expenditure and, not surprisingly, multiple studies indicate that individuals with spinal cord injury have lower physical activity levels than those without, tetraplegia is associated with lower activity levels than paraplegia, and participation in athletic activities is decreased.^{15,20} Bucholz and colleagues recorded total daily energy expenditure over a three-day period and concluded in their study that “subjects” mean physical activity levels were (1) consistent with the World Health Organization’s definition of limited activity, (2) lower than levels previously reported in able-bodied adults, and (3) similar to those of adults with hereditary neuromuscular disease and cerebral palsy. This was the case despite 56% of participants having engaged in structured physical activity an average of 1.5 times during the observational period, for an average of 49 ± 31 minutes per session.”¹⁵ In this same study by Bucholz, researchers noted a significantly lower activity level (18% lower) in subjects with complete lesions than with incomplete lesions. Additionally, patients

with tetraplegia have a clear disadvantage regarding maintenance of daily physical activity levels.

Based on our understanding of these three components of total daily energy expenditure of the spinal cord injury patient, it can be extrapolated that caloric requirements should be estimated based on fat-free mass. Although additional studies are required to clarify the thermic effect of food, it can safely be recommended that SCI patients be encouraged to engage in physical activity regularly with a likely increase in frequency, intensity and duration when possible. Further research to clarify recommendations regarding the optimization of each of these three components of total daily energy expenditure would be beneficial as would efforts to clarify their relationship to neurologic level of injury.

In addition to obesity, osteoporosis is a major concern to management of the spinal cord injury patient. This form of osteoporosis differs from that of menopausal women due to the neurogenic component of its origin. Debate exists regarding its identification as well as management in this patient population and significant complications can result from its presence including long bone fractures.

Regarding the development of osteoporosis in the spinal cord injury patient, studies of bone metabolism indicate that there is a progressive elevation of bone resorption marker levels from the first week post injury onward, peaking between 3 and 6 months later. There has been an imbalance between these markers and bone formation markers which indicate the presence of bone loss. A decrease in bone mineral density is measureable from approximately 12 months onward; and, bone metabolism arrives at a new stable state at 16 months.²¹ Additionally, neurologic level determines extent of demineralization with tetraplegics affected in upper and lower extremities while the lower limbs of paraplegics are only generally affected.

Currently, the diagnosis of osteoporosis is based on determination of bone mineral density. It may be of benefit to measure bone density in regions commonly fractured in the spinal cord injury patient (including areas comprised of trabecular rather than cortical bone such as the distal femur or proximal tibia) as suggested by Shields in 2005. Biochemical markers, however, may offer information earlier in the process of the development of osteoporosis than measurement of bone mineral density. In their study, Maimon et al. revealed that bone mineral density testing in their cohort of seven patients (injured on average three

months prior to evaluation) did not detect a variation during this acute stage; however, biochemical markers of bone turnover were significantly increased including calciuria, decreased serum intact PTH, and $1.25(\text{OH})_2$ vitamin D levels.²² Therefore, blood and urine biochemical profiles may be useful in screening spinal cord injury patients for metabolic changes related to the development of osteoporosis. Craven et al. noted that frequently assayed markers of bone turnover including osteocalcin, N-telopeptide, and hydroxyprolinuria may be affected by mechanism of injury since many spinal cord injuries are associated with vertebral fracture.²³ The process of fracture healing can alter the levels of these markers for months, possibly making them less than ideal for use in the screening process for osteoporosis in the early period (first 3–6 months) following traumatic injury.

Regarding treatment of osteoporosis in the spinal cord injury patient population, the first step is to optimize nutritional status, and ensure that patients are receiving an adequate amount of vitamin D. According to Briot et al. the minimum recommended serum level of vitamin D is 30 ng/mL.²⁴ In their study Neumanaitis et al. concluded that inadequate or severely deficient levels of vitamin D-25(OH) were highly prevalent in patients with spinal cord injury admitted to an acute inpatient rehabilitation service; and, evaluation of serum vitamin D levels are recommended in patients with SCI since low levels may contribute to osteoporosis.²⁵ Bauman et al. recognized in their study that administration of a vitamin D analogue had a significant effect on the maintenance of leg bone mineral density in their cohort of 40 tetraplegic spinal cord injury patients.²⁶ Bauman et al. also noted in a study published in *The Journal of Spinal Cord Medicine* in 2011 that a daily prescription of 2000 IU of oral vitamin D(3) for 3 months safely raised the serum 25(OH)D levels into the normal range in persons with chronic SCI on 1.3 g of calcium daily.²⁷ Administration of vitamin D and calcium supplements are potentially helpful in the management of the compliant patient and are a recommended first step in the prevention of osteoporosis in this patient population.

Based on research reviewed, it appears that the role of bisphosphonate therapy in the treatment of neurogenic osteoporosis remains to be elucidated. According to Bryson's review of seven studies, "data were insufficient to recommend routine use of bisphosphonates for fracture prevention in spinal cord patients... Uniform bone density measurement sites with rigorous quality control and compliance monitoring are needed to improve reliability

of outcomes.”²⁸ Bryson’s criticisms of the studies she reviewed include sample size and confounding variables including inconsistency of calcium and vitamin D supplementation. Also, these studies tend to include a small number of patients and do not incorporate fracture outcomes. Regardless, certain studies have shown a decrease in the rate of decline in bone mineral density of patients with SCI with oral alendronate administered within ten days of SCI followed by weekly 70 mg doses for 12 months.²⁹ Additionally, research involving administration of a single 4 or 5 mg dose of zoledronic acid (given within ten to twelve weeks following injury) demonstrated attenuated bone loss at the proximal femur for 6 months and the distal femur for 12 months in the treatment group when compared with those administered a placebo.³⁰ Based on results such as these, bisphosphonate therapy may potentially aid the management of SCI patients suffering from osteoporosis; however, at this time, further research is necessary to clarify optimal treatment strategies and potential benefits to fracture prevention.

FUTURE DIRECTIONS

Levels of osteoprotegerin have been studied in spinal cord injury patients. Osteoprotegerin is part of the RANK/RANKL system and inhibits bone resorption. In their study, Morse et al. noted that serum osteoprotegerin levels correlated with severity of spinal cord injury and hypothesized that it might be possible to prevent post-SCI bone loss by the administering recombinant osteoprotegerin.³¹ Sclerostin is a protein synthesized by osteocytes which exerts regulatory effects on bone formation by osteoblasts.³² Recent trials (performed in monkeys) demonstrated that injection of antisclerostin antibody increased bone formation and density. Results of these studies also suggested that antisclerostin antibody had a positive effect on bone resistance and architecture.³³ Further research regarding the mechanism of bone loss in SCI patients and potential routes to directly limit such a process would be necessary to clarify treatment protocols and the relevance of medications such as antisclerostin antibody or recombinant osteoprotegerin. Valid treatment regimens for osteoporosis resulting from spinal cord injury may prove to be quite different than those developed for the management of post menopausal osteoporosis.

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Rehabilitation of the Spinal Cord Injury Patient

Jesse D Ennis, Rhonda Willms, Andrea Townson

Snapshot

- » Epidemiology
- » Neurologic Assessment in SCI Rehabilitation
- » Prognosis
- » Late Deterioration
- » Pain in SCI
- » Bladder Management
- » Bowel Management
- » Cardiovascular Complications

INTRODUCTION

The diagnosis of a spinal cord injury (SCI) brings with it a lifetime of additional challenges that go beyond the difficulties of muscle paralysis and sensory loss. Rehabilitation addresses the physical, medical, psychological, and social needs that arise as a result of this significant injury.

Early comprehensive interdisciplinary rehabilitation lays the foundation for improved functional outcomes in patients with SCI. The goals of rehabilitation following SCI are to maximize neurologic and functional recovery, to prevent secondary complications, and to assist the patient with community reintegration.

Rehabilitation specialists should be involved immediately following SCI.¹ In the first hours to days, emphasis should be on the acute management of the patient and stabilization of medical status. Early acute rehabilitation starts when the patient can participate fully in a rehabilitation program and concludes with successful community reintegration. For patients with traumatic SCI, early referral to a specialized acute care center reduces mortality, morbidity, and length of stay in acute care.^{2,3} Patients referred to integrated systems of SCI care have better functional outcomes, fewer secondary complications, and shorter hospitalizations.^{1,4-8} After the acute rehabilitation phase, regular long-term follow-up provides the ongoing ability to prevent and monitor secondary complications.

The interdisciplinary rehabilitation team consists of rehabilitation physicians, nurses, occupational and physical therapists, social workers, and psychologists working with patients and their families to maximize functional recovery. Other health care professionals may also be involved with patients throughout their rehabilitation.

After discharge into the community, regular, specialized continuing follow-up care is important to reduce the risks of secondary complications and to ensure the success of community reintegration. Patients with SCI have high rates of rehospitalization, particularly during the first year following discharge.^{9,10} The importance of follow-up is highlighted by the fact that the leading causes of rehospitalization include potentially preventable secondary complications such as urinary tract infections, pressure ulcers, and respiratory infections.

EPIDEMIOLOGY

Spinal cord injury can be categorized as traumatic or non-traumatic in origin. While traumatic SCI has been studied more than nontraumatic SCI, recent studies suggest that nontraumatic SCI may be more common than traumatic injuries in some regions.¹¹

The incidence of traumatic SCI varies from 15 per million in Australia and Western Europe to 35 per million in Canada and 39 per million in the United States.^{12,13}

The most common causes of traumatic injuries are motor vehicle collisions, falls, sports injuries, violence, self-harm, and work-related accidents. In older individuals, falls are the leading cause of traumatic SCI.¹⁴

Over time, the mean age of patients at time of injury has been increasing. Men have continued to be disproportionately affected, with 77.1% of new injuries occurring in males since 2000 in the United States. However, in elderly patients with SCI, the proportion of men to women affected is nearly equal.¹⁵ The prevalence of traumatic SCI has generally increased over time, which may reflect increasing life expectancy after SCI or increasing incidence.¹⁴

With regard to nontraumatic SCI, it appears that the incidence has been increasing over time.¹⁶ In a recent Australian cohort study, the proportion of nontraumatic SCI sampled from a national rehabilitation database was 62%.¹¹ Data is limited on frequency of etiology in nontraumatic SCI, but one study from South Korea demonstrated causes in order of frequency to be tumor, spinal stenosis, transverse myelitis, arteriovenous malformation, infection, spinal cord infarction, and epidural hemorrhage.¹⁶ Compared with traumatic SCI, those with a nontraumatic etiology tend to have a more equal distribution between sexes, older age at onset, and greater proportion of paraplegia, and have shorter in-patient rehabilitation admissions. At the same time, they appear to achieve a similar level of function on discharge from a rehabilitation program.¹¹

NEUROLOGIC ASSESSMENT IN SCI REHABILITATION

Neurologic assessment of patients with SCI is important for rehabilitation planning, for monitoring neurologic outcomes, and for predicting neurologic and functional prognosis. The neurologic assessment is performed using the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI).¹⁷ The ISNCSCI examination is a focused neurologic examination consisting of three primary components: a sensory examination, a motor examination, and an autonomic standards assessment. Training modules for the examination are available online through the American Spinal Injury Association (ASIA) website (<http://asia-spinalinjury.org/learning>). Using the ISNCSCI standards, both a neurologic level and degree of injury completeness can be determined. The neurologic level of injury (NLI) is defined as the most caudal level with intact bilateral sensory and motor function. The degree of injury completeness is determined using the ASIA impairment scale (AIS) (Table 62.1).

Table 62.1: The ASIA impairment scale.¹⁷

ASIA impairment scale	Injury completeness	Definition
A	Complete	No sensory or motor sparing occurs in the sacral (S4–S5) segments
B	Sensory incomplete	Sensory function only is preserved in the sacral segments and no motor function is preserved more than three levels below the motor level on either side
C	Motor incomplete	Motor function is preserved below the neurological level* and more than half the muscles below the neurologic level of injury (NLI) are less than Grade 3 strength
D	Motor incomplete	Motor function is preserved below the neurological level* and at least half the muscles below the NLI are Grade 3 or above
E	Normal	In a patient with a spinal cord injury and prior deficits with a now completely normal International Standards for Neurological Classification of Spinal Cord Injury examination

*For patients to be assigned motor incomplete status they must have either voluntary anal contraction OR sacral sensory sparing with some preserved motor function more than three levels below the motor level on either side of the body.

The sensory examination includes bilateral assessment of dermatomes C2 through S4–S5, using both light touch and pinprick sensory modalities. The sensory level is the most caudal level with intact sensation in both modalities. The motor examination includes bilateral examination of one key muscle for each myotome from C5 to T1 and from L2 to S1. Motor grading is performed using the Medical Research Council grades from 0 to 5.

The motor level is the most caudal level with at least Grade 3 strength, as long as all myotomes above the level have Grade 5 strength. A rectal examination is performed to assess both for sensation of deep anal pressure and for voluntary anal contraction, which are important for determining whether the injury is sensory or motor sparing.^{17,18} A complete SCI is defined as an injury where there is no sparing in the lowest sacral segments as determined by the rectal examination.

Based on the guidelines of the Paralyzed Veterans of America, an initial neurological assessment should be performed as soon as possible, but within a maximum of 6 hours after a suspected SCI to confirm a diagnosis. Following this, a detailed examination using the ISNCSCI protocol should be performed between 72 hours from the time of injury to 7 days from the injury for prognostic purposes.¹⁹ Detailed assessments performed for prognosis at 48 hours may not have the same accuracy as a 72-hour examination due to the potential confounding presence of spinal shock.²⁰

Periodic reassessment is required until neurological recovery has reached a plateau. Typically, recovery after SCI is most rapid in the first 6 months post-injury. After 3–6 months, recovery speed slows significantly; however, there may be some recovery up to 2 years or even longer after injury.¹⁹

PROGNOSIS

Discussing prognosis with patients and their families is an important part of caring for individuals with SCI. Many patients will specifically want to know if they will walk again, but it is also valuable to have an appreciation of expected global outcomes by the level of injury. Most studies evaluating the use of the ISNCSCI standards for prognosis have been for patients with traumatic SCI. The use of the standards as a prognostic tool for nontraumatic SCI has not been as well studied. However, to date, studies comparing all-cause nontraumatic, ischemic, and even neoplastic SCI to traumatic SCI have not found significant differences in the degree of neurologic function on discharge from a rehabilitation unit. These studies have typically used statistical methods to correct for baseline differences in these populations, given that there are significantly lower rates of complete injuries in patients with a nontraumatic etiology compared to traumatic injuries.^{21–24}

The AIS, when determined at 72 hours post-injury, is very stable over time. In individuals categorized as AIS A at 72 hours, 80% will remain AIS A at the time of discharge from inpatient rehabilitation, with 10% converting to AIS B, and another 10% converting to AIS C.²⁰ Overall, the most important prognostic indicator is neurologic status at the time of initial assessment. Additional positive prognostic factors include younger age at time of injury, preservation of pinprick in sensory sparing injuries, and the length of time from injury to admission to a rehabilitation unit.^{20,22} Evidence of spinal cord hemorrhage on magnetic resonance imaging is a negative prognostic indicator for

Table 62.2: Prediction of functional ambulation by ASIA impairment scale.²⁰

ASIA impairment scale	Additional features	Percent functional ambulators at 1 year (%)
A	Cervical lesion	0
	Thoracic/lumbar lesion	5–8.5
B	Only light touch spared	0–33
	Light touch and pinprick spared	66–89
C	Less than 50 years old	71–91
	Greater than 50 years old	25–42
D	Less than 50 years old	100
	Greater than 50 years old	80–100

Source: Adapted from Scivoletto G, Di Donna V. Prediction of walking recovery after spinal cord injury. *Brain Res Bull.* 2009;78(1):43–51.

functional recovery and is associated with a greater proportion of complete injuries when found. Conversely, spinal cord edema tends to be correlated with a greater degree of recovery and is associated with incomplete injuries when it is present in the absence of hemorrhage. However, as the degree of edema increases, the prognosis worsens.²⁰

An overall prediction for recovery of ambulation by AIS grade is presented in Table 62.2. Functional ambulation is typically defined as walking a reasonable distance in and out of the home, and frequently will require the use of gait aids and lower extremity orthotic devices.

LATE DETERIORATION

It is important to continue to monitor patients with SCI to detect any evidence of neurologic deterioration. A decline in function or a progression of the NLI after an injury should raise concern about the possibility of spinal cord tethering or syringomyelia. Other causes of late neurologic deterioration include the development of peripheral nerve entrapments, such as carpal tunnel syndrome.¹⁹

Syringomyelia has an estimated prevalence of 21–28% within 30 years of the initial injury. However, only 1–9% of patients with syringomyelia post-SCI will be symptomatic, which mandates a careful clinical assessment to correlate symptoms to imaging findings. Symptoms include loss of

pain and temperature sensation, with relatively preserved proprioceptive and vibratory sensation, pain at or above the level of the lesion, and asymmetric progressive weakness. If the syringomyelia involves the brainstem, bulbar findings may be noted on examination of the cranial nerves. Typically, surgical intervention is considered in the context of progressive neurologic deterioration or pain associated with evidence of syringomyelia.²⁵

■ PAIN IN SCI

Pain is a frequent and significant complication of SCI. Prevalence estimates of pain after SCI have demonstrated a very wide range in the literature, from 26% to 96%, with 30–40% of SCI patients experiencing disabling pain.²⁶ The onset of pain is generally within the first 6–12 months after injury.²⁷ Patients with a low spinal cord or cauda equina lesion are more likely to report severe pain than others.²⁷

The International Classification of Spinal Cord Injury Pain proposes classifying pain in SCI as either neuropathic or nociceptive. Neuropathic pain is divided into at-level, below-level and other pain, whereas nociceptive pain is divided into somatic, visceral, and other pain.^{28,29} Although neuropathic pain is often due to the primary or secondary injury to the spinal cord, nociceptive pain may develop after the injury. In particular, musculoskeletal nociceptive pain involving the upper extremities is common, occurring in 58.5–72.7% of patients with SCI. Upper extremity pain may be attributed to chronic upper extremity overuse from wheelchair propulsion and transfers.²⁷

The management of pain after SCI can be approached with stepwise use of nonpharmacological, pharmacological, and even surgical measures. The initial step is taking a thorough pain history and establishing the etiology of the pain. It is particularly important to identify nociceptive pain sources, where an underlying disease needs to be treated in addition to treating the pain.

Other factors such as decubitus ulcers, infections, autonomic dysreflexia (AD), spasticity, mood or anxiety disorder, and renal calculi may worsen pain post-SCI.²⁷ In particular, it is important to consider a diagnosis of syringomyelia when a patient presents with new pain.³⁰

Nonpharmacological treatments such as hypnosis, visual imagery, and transcranial electrical or magnetic stimulation all have varying levels of evidence in the treatment of pain after SCI.^{27,31}

Gabapentinoids are the first-line pharmacologic treatment of neuropathic pain following SCI. While tricyclic antidepressants and serotonin–norepinephrine reuptake inhibitors are generally recommended for the treatment

of neuropathic pain, there is surprisingly limited evidence for their use in post-SCI neuropathic pain.^{27,30,32} Third- and fourth-line agents such as opioid analgesics and cannabinoids have some evidence for use following SCI. Cannabinoids may have promise in this patient group, given that other studies have demonstrated efficacy in other patient populations with central neuropathic pain.^{27,30} There is also evidence for the use of topical capsaicin, intrathecal clonidine in combination with morphine, intravenous ketamine, and the short-term use of lidocaine via subarachnoid lumbar catheter as treatments of post-SCI pain.²⁷

Finally, surgical approaches including spinal cord stimulation, dorsal longitudinal T-myelotomy, and dorsal rhizotomy/dorsal root entry zone (DREZ) procedures can be considered. There is little evidence to support the use of spinal cordotomy. There is no evidence to support the use of sympathectomy for the treatment of post-SCI pain.^{27,30}

■ BLADDER MANAGEMENT

Sexual Health

Renal failure was once the leading cause of death after SCI. Today, as a result of improvements in bladder care, renal failure accounts for only 3% of deaths post-SCI.³³ However, despite these gains, the importance of good neurogenic bladder management following SCI cannot be underestimated.

Almost all patients with SCI have neurogenic bladders. The type of bladder dysfunction depends on both the level and the completeness of injury. No matter what type of bladder dysfunction is present, the goals of management are the same: to preserve renal function, minimize urinary tract complications, and provide bladder management compatible with a patient's lifestyle.³³

During the acute phase post-injury, patients should have an indwelling urinary catheter placed until they are hemodynamically stable and no longer require strict fluid monitoring.¹ Once urinary output has stabilized, the preferred bladder management option is intermittent catheterization.³⁴ Intermittent catheterization should be performed every 4–6 hours, with target bladder volumes of <500 mL. Unfortunately, despite significant evidence that intermittent catheterization is the safest and healthiest long-term bladder management technique, compliance may often be an issue, with up to 42% of patients discontinuing this technique in the long-term.³⁵

Indwelling catheters should be considered in patients who are unable to manage their bladders with intermittent catheterization. Both urethral and suprapubic catheters are associated with increased rates of infection, as well as renal and bladder calculi.³³ Due to the increased risk of bladder cancer in patients with long-term indwelling catheters, patients with indwelling catheters should undergo regular screening cystoscopy.³⁶

Pharmacotherapy for patients is aimed at reducing incontinent episodes, while maintaining low bladder pressures, using agents such as anticholinergics, α -adrenergic antagonists, and intravesicular botulinum toxin type A.^{34,37}

Urinary tract infections are a frequent complication. Symptoms and signs include pyuria, discomfort or pain over the kidneys or bladder, dysuria, new onset incontinence, increased spasticity, cloudy urine with increased odor, malaise, lethargy, or a sense of unease.³³ Frequent, unexplained infections should prompt a search for a renal or bladder calculus.³⁸

Yearly evaluation of the upper and lower tracts is important in order to exclude changes in the urologic system that would indicate high-pressure voiding or renal calculi. Clinical history and symptoms may not correlate well to the degree of urologic dysfunction, and the goal of treatment is to keep bladder pressures below 40 cm H₂O in order to prevent long-term renal complications.³³ Urodynamics are an important component in monitoring response to treatment in patients and avoiding long-term complications. Up to two thirds of patients with an SCI demonstrate urologic deterioration on urodynamics in long-term follow-up, despite no change in their clinical status.³⁹

BOWEL MANAGEMENT

Sexual Health

Neurogenic bowel dysfunction is a frequent complication of SCI. Up to 95% of patients with SCI will have some degree of bowel dysfunction, and the same number of individuals will require at least one therapeutic intervention in order to defecate.^{40,41} This issue is severe enough to affect quality of life in 62% of individuals.⁴² The most common complications of bowel dysfunction include constipation, fecal impaction, hemorrhoids, and incontinent episodes.⁴⁰

Neurogenic bowel dysfunction can be divided into two different patterns. In injuries above the conus medullaris, there is a pattern of an upper motor neuron (UMN)

bowel characterized by increased colonic wall and anal tone, loss of cortical control of the external anal sphincter, and spastic external anal sphincter. This pattern is predominated by constipation and fecal retention. In injuries at the conus medullaris or cauda equina, there is a lower motor neuron (LMN) bowel with severely prolonged colonic transit time, atonic external anal sphincter, and absent control over the puborectalis and other levator ani muscles. This leads to constipation as well, but additionally carries a very high risk of fecal incontinence.

Several guidelines have been developed for the approach to bowel management, including guidelines by the Consortium for Spinal Cord Medicine and by the Multidisciplinary Association of Spinal Cord Injury Professionals.^{41,43} Both guidelines advocate a stepwise approach, beginning with history and physical examination to determine whether a patient has an UMN or LMN bowel pattern. Overall goals include the establishment of regular bowel care to allow for complete colonic evacuation and the prevention of incontinent episodes. General dietary recommendations start with an intake of 15 g of fiber per day and 40 mL/kg plus 500 mL of fluid daily.^{41,42}

For UMN bowel management, the approach typically utilizes local reflexes to initiate bowel movements with either digital stimulation or a chemical suppository.⁴² If evacuation is incomplete, manual disimpaction can be used to ensure a complete bowel movement. If stool consistency is too firm, oral laxatives can be added to the regimen. Although there is no clear body of evidence, often osmotic laxatives such as polyethylene glycol are used on a regular basis, with stimulant laxatives, such as bisacodyl or sennosides, used on an as-needed basis.^{4-6,41} For any patient who is prone to AD, local anesthetic gel should be applied to the anus several minutes prior to digital stimulation or insertion of suppositories to avoid triggering AD.^{41,43}

For an LMN bowel, the approach is manual disimpaction on a regular basis, ideally once daily or less, if continence can be maintained. Additional measures such as digital stimulation and the use of suppositories are typically not effective in this population due to a loss of local colonic reflexes.

For patients who consistently do not respond to conservative measures, more intensive approaches exist. Transanal irrigation and pulsed water irrigation both use water to remove stool from the descending colon. Both have shown efficacy in relieving constipation and incontinence in neurogenic bowel.⁴² For patients who do not tolerate noninvasive approaches, the Malone antegrade

continence enema procedure has demonstrated efficacy. This procedure creates an anastomosis between the appendix and cecum with a continent stoma, allowing tap water enemas to be inserted that stimulate colonic motility and emptying.⁴² There is also evidence for implanted sacral nerve root stimulators in otherwise refractory populations.⁴² Colostomy can be a safe and effective treatment of severely affected patients, and has been found to improve both quality of life and persistent perianal pressure ulcers based on case studies, pre-post studies, and retrospective reviews.⁴² However, a recent decision analysis study suggested that among the Malone procedure, sacral stimulation, and colostomy, the Malone procedure was the best option; this has yet to be confirmed with direct clinical trials.⁴⁴

Additional acute gastrointestinal complications of SCI include reflex ileus (4.6%), peptic ulcers (1.4%), and pancreatitis (2.2%). These are most common in the first month post-injury. Given the altered sensation in patients with SCI, these conditions may present atypically, and a high index of suspicion should be maintained in the event of nonspecific clinical deterioration.⁴¹

CARDIOVASCULAR COMPLICATIONS

Respiratory Complications

Acute Injury

After acute SCI, the most common cardiovascular effect is acute hypotension with bradycardia. Initial management steps include IV fluid resuscitation, pressors and supportive care, until the period of neurogenic shock is over.¹

Venous Thromboembolism Prophylaxis

The incidence of early deep vein thrombosis (DVT) in acute SCI has been reported to be above 50% without treatment, with fatal pulmonary embolism (PE) occurring in as many as 5%.⁴⁵ While the highest risk of DVT is within the first 2 weeks following an acute SCI, DVT prophylaxis needs to continue throughout the rehabilitation phase. The clinical diagnosis of DVT is unreliable, and, accordingly, a high index of suspicion must be maintained.

Mechanical and pharmacological DVT prophylaxis should be initiated as early as possible. Mechanical compression devices are generally recommended for at least 2 weeks.^{46,1} Low-molecular-weight heparin (LMWH) should be initiated within 72 hours of injury in all patients

with SCI.^{1,47,48} Low-molecular-weight heparin should be held on the morning of surgery and resumed within 24 hours following surgery.⁴⁷ In motor complete injuries, LMWH should be continued at prophylactic doses for 8–12 weeks from the time of injury.^{45,48} In motor incomplete injuries, patients with AIS C injuries should receive LMWH for 8 weeks, and patients with AIS D injuries should receive anticoagulants for the length of their rehabilitation stay.⁴⁶ For patients who fail anticoagulant therapy, or who have a contraindication to anticoagulation, an inferior vena cava filter should be considered to prevent PE. Although studies are lacking, once a DVT is established, treatment is typically started with IV unfractionated heparin or full-dose LMWH. After transition to warfarin, full anticoagulation is maintained for 3–6 months.^{45,46}

Autonomic Dysreflexia

Autonomic dysfunction is common after SCI, thus leading to issues of AD and orthostatic hypotension (OH). AD is a medical emergency and must be treated aggressively. It occurs due to loss of central nervous system modulation of the sympathetic nervous system in individuals with SCI at the level of T6 or above. As a result, any noxious or inciting stimulus below the level of the injury may trigger excessive peripheral sympathetic outflow, leading to splanchnic vasoconstriction and a hypertensive emergency. An episode of AD is characterized by an elevation of blood pressure (BP) 20–30 mm Hg above baseline and is frequently associated with bradycardia due to unopposed vagal stimulation. It is important to recognize that AD may be occurring in a patient with a “normal” BP since resting systolic BP is between 90 and 110 mm Hg in patients with tetraplegia. Initial symptoms of AD may include headache, flushing and sweating above the level of the lesion, anxiety, nasal congestion, blurred vision, cardiac arrhythmias, and cool dry skin below the lesion. The consequences of untreated episodes of AD may be cerebral hemorrhage, cardiac complications, retinal detachment, seizures or death.^{49,50}

The treatment of AD is primarily directed at determining and eliminating the trigger of the episode. The most frequent cause of an episode is urinary retention or fecal impaction, and these should be checked first. Other causes are numerous and are included in Table 62.3.⁵⁰ After recognition of an episode, patients should be sat up in bed and have constrictive clothing loosened. BP and pulse should be monitored every 5 minutes while the bladder and bowel are being checked. If symptoms persist despite

Table 62.3: Causes of autonomic dysreflexia.⁵⁰

System	Causes
Genitourinary	Bladder distention Bladder or kidney stones Blocked catheter Catheterization Urologic instrumentation Detrusor sphincter dyssynergia Shock wave lithotripsy Urinary tract infection
Gastrointestinal	Appendicitis Bowel distention Bowel impaction Gallstones Gastric ulcers or gastritis GI instrumentation Hemorrhoids
Skin	Constrictive clothing, shoes, or appliances Contact with hard or sharp objects Blisters Burns, sunburn or frostbite Ingrown toenail Insect bites Pressure ulcers
Reproductive	Sexual intercourse Sexually transmitted infections Ejaculation Epididymitis Scrotal compression (sitting on scrotum) Electroejaculation and vibratory stimulation to induce ejaculation Menstruation Pregnancy Vaginitis
Other	Boosting (an episode of autonomic dysreflexia intentionally caused by an athlete with spinal cord injury in an attempt to enhance physical performance) Deep vein thrombosis or pulmonary embolism Excessive alcohol intake Excessive caffeine or other diuretic intake Fractures or other trauma Functional electrical stimulation Heterotopic bone Over-the-counter or prescribed stimulants Substance abuse Surgical or invasive diagnostic procedures

catheterization and bowel care, a search for other potential causes of AD needs to be undertaken. If systolic BP remains elevated above 150 mm Hg, a short-acting antihypertensive

should be considered. The most frequently used agents include nifedipine and topical or sublingual nitrates. In recent years, the use of nifedipine has been discouraged due to the risk of severe hypotension in other patient populations, although no adverse events have been reported in SCI patients. Other options include prazosin and captopril.⁴⁹⁻⁵¹

Orthostatic Hypotension

Orthostatic hypotension occurs in over 70% of patients, with 59% of them being symptomatic.⁵² It is defined as a 20 mm Hg drop in systolic BP or a 10 mm Hg drop in diastolic BP.⁴² Orthostatic hypotension is particularly common in the first month post-SCI, occurring in 74% of cervical and 20% of upper thoracic motor complete injuries.⁵³ First-line treatment is nonpharmacologic and includes increasing salt and fluid intake, avoiding diuretics, avoiding large infrequent meals, and using abdominal binders and compression stockings. In addition, maintaining the head of the bed at 20–30° may increase orthostatic tolerance over time.⁵² Although commonly recommended, many of these approaches have a relative absence of evidence.⁴² If symptomatic OH persists, pharmacological treatments include midodrine, an α -adrenergic agonist, and fludrocortisone, a mineralocorticoid.⁵² Overall, there is more evidence for the efficacy of midodrine, and it should be used in preference to fludrocortisone, but with careful attention to symptoms of AD.⁴²

Metabolic Syndrome

Metabolic syndrome and cardiovascular disease occur more frequently in patients with SCI than in healthy controls. On average, patients with SCI have lower lean body mass, higher glucose and insulin levels, and higher lipid levels.^{54,55} Overall, these effects may contribute to premature coronary artery disease and diabetes in patients with SCI.⁵⁶ The risk of developing cardiovascular disease is higher in patients with higher level injuries and complete injuries. In one study of patients with complete tetraplegia, 84% of asymptomatic patients had signs of coronary artery disease on nuclear medicine stress testing.⁵⁷ This highlights the need to engage patients with SCI in some form of lifelong aerobic exercise program. This can be challenging especially for patients with complete tetraplegia. Current physical activity guidelines for adults living with SCI suggest at least 20 minutes of moderate-vigorous aerobic activity two times per week, as well as strength training exercises two times per week.⁵⁸

Respiratory Complications

Long-term Complications

Respiratory complications, such as atelectasis, pneumonia and respiratory failure, account for a significant portion of chronic morbidity and mortality in SCI. There is a global decline in all lung volumes that is more pronounced progressively with higher level injuries.⁵⁹ Injuries at C5 and above cause diaphragmatic dysfunction that may lead to respiratory muscle fatigue and the need for mechanical ventilation. In patients with a level of injury at C2 and above, if there is preservation of the phrenic nerve and nucleus, diaphragmatic or phrenic nerve pacing may be an option in order to avoid long-term mechanical ventilation.^{59,60} For individuals with intact diaphragmatic function, there is impairment of the external intercostal and abdominal muscles, which are important for generating cough. Accordingly, even patients with paraplegia are at risk for long-term respiratory complications.⁵⁹

For individuals not requiring long-term invasive ventilation, there are several components to respiratory management. To clear secretions, and slow further decline in lung volumes, physical techniques are used. For secretions, postural drainage, manually assisted cough and insufflation-exsufflation devices may be used. To maintain lung volumes, lung volume recruitment techniques several times daily are important. These typically use a Bag-Valve-Mask to “stack” multiple breaths and expand lung volumes passively.⁵⁹

An additional chronic concern is the development of obstructive sleep apnea (OSA), which occurs at a rate of 25–45% in the SCI populations, compared to 2–4% in the general population.^{59,61} It appears that the increased rates of OSA may be due to weight gain due to inactivity, the use of antispasmodics such as baclofen, or the development of airway resistance because of reduced lung volumes. Patients with symptoms of OSA, such as morning headache and daytime somnolence, should be screened with overnight oximetry and formal sleep studies.⁵⁹

Spasticity

Long-term Complications

Up to 70% of patients with SCI develop spasticity severe enough to cause some degree of functional impairment.⁶² For up to 41% of patients, spasticity may be a major obstacle preventing community reintegration.⁶³ Spasticity has

been defined by Lance as “a motor disorder characterized by a velocity-dependent increase in tonic stretch reflexes (muscle tone) with exaggerated tendon jerks, resulting from hyperexcitability of the stretch reflex.”^{62,64} Despite this narrow definition, the term spasticity is often used to describe related findings that are a result of an UMN injury, such as hyperreflexia, clonus, prolonged cutaneous reflexes, and muscle spasms. It is this overall category of phenomenon that is of concern as it relates to patients with SCI.

Given that most individuals with SCI develop spasticity, it is important to consider whether there is a functional impairment caused by the increased tone. Problems associated with severe uncontrolled spasticity may include contractures, improper posture, pressure ulcers, and pain. However, mild spasticity may improve function by allowing patients with limited volitional motor function to transfer and stand and by lessening skeletal muscle atrophy.^{62,63}

Once spasticity is identified, it is important to rule out secondary causes of increased tone. Any noxious stimulus can manifest as an increase in spasticity. This includes constipation, pneumonia, urinary tract infection, ingrown toenails, pressure ulcers, menses and intra-abdominal pathology. Acute sepsis and syringomyelia should also be considered as potential causes of increased spasticity.⁶²

Treatment should be initiated if there are specific functional goals that may be achieved by reducing spasticity. Treatments cross the spectrum from noninvasive strategies, to pharmacotherapy, interventional and surgical approaches.

Noninvasive management includes regular stretching, physical activity, and therapeutic standing.⁶² Evidence does exist to support additional therapies such as electric passive cycling, assisted standing, and a neural facilitation activity approach.⁶³ Pharmacotherapeutic options include baclofen, tizanidine, dantrolene, benzodiazepines, gabapentinoids, and cannabinoids. Baclofen is a GABA analog that inhibits spinal neurons pre- and post-synaptically, and is generally considered the first-line agent for the treatment of spasticity in SCI.⁶³

Interventional options include focal chemodenervation using botulinum toxin or phenol.⁶³ Intrathecal baclofen therapy uses an implanted pump device to deliver very small doses of baclofen directly to the intrathecal space. It is considered for patients with severe, functionally limiting spasticity who do not respond to other treatments. Although complications may be severe in the event of

acute baclofen withdrawal, this occurs at a low rate, making it a very effective option for some patients.⁶³

Surgical options for patients include direct spinal cord stimulation via an epidural cord stimulator and spinal myelotomy. There is limited evidence from pre-post studies that spinal cord stimulation may provide spasticity relief for patients with intractable spasticity, but the duration of effect is not clear. Dorsal longitudinal T-myelotomy may result in reduced spasticity based on a single low-quality RCT and a single case series in patients with spasticity who did not respond to nonsurgical measures.⁶³ Other surgical interventions are aimed at reducing the orthopedic complications of spasticity. These include tendon lengthening, tendon plasty and osteotomy. These are typically performed for local spasticity that has not responded to other treatments, or for established contractures.⁶²

Pressure Ulcers

Long-term Complications

Pressure ulcers are estimated to be one of the most frequent and costly complications after SCI.⁶⁵ The annual incidence of pressure ulcers has been estimated at 20–31%, with ulcers occurring at any stage of injury from the acute to chronic phase.^{66,67} The primary inciting event in ulcer formation is often an elevation in pressure and shear forces. The forces of direct pressure cause ischemia by restricting flow through skin and soft tissue capillaries. Shear forces, which are applied in parallel to the affected tissue, also lead to ischemia, but affect penetrating vessels running perpendicular to the skin's surface. In addition to mechanical forces, patients with SCI may be more susceptible to ulceration due to biochemical alterations in skin and soft tissue structure.⁶⁷ Adding to this, patients with SCI have impaired sensation and often have compromised ability to shift the weight. Additional risk factors for the development of pressure ulcers include limitation in activity and mobility, smoking, complete injuries, bowel and bladder incontinence, muscle atrophy, poor nutritional status, male sex, lower education and socioeconomic status, comorbid medical conditions, anemia and hypoalbuminemia, spasticity and history of prior pressure ulcers.⁶⁶

The first sign of a pressure ulcer is a change in the skin appearance. However, underlying soft tissues such as muscle are actually more susceptible to ischemia. Accordingly, the injured skin may be thought of as the “tip of the iceberg,” which signals more significant damage below.⁶⁷ Table 62.4 outlines the National Pressure Ulcer Advisory

Table 62.4: National Pressure Ulcer Advisory Panel's (NPUAP) updated pressure ulcer staging system (NPUAP 2007).⁶⁸

Stage	Description
Deep tissue injury (suspected) stage	Purple or maroon localized area of discolored intact skin or blood-filled blister due to damage of underlying soft tissue from pressure and/or shear. The area may be preceded by tissue that is painful, firm, mushy, boggy, warmer or cooler as compared to adjacent tissue
Stage I	Intact skin with nonblanchable redness of a localized area usually over a bony prominence. Darkly pigmented skin may not have visible blanching; its color may differ from the surrounding area
Stage II	Partial-thickness loss of dermis presenting as a shallow open ulcer with a red pink wound bed, without slough. May also present as an intact or open/ruptured serum-filled blister
Stage III	Full-thickness tissue loss. Subcutaneous fat may be visible but bone, tendon or muscle are not exposed. Slough may be present but does not obscure the depth of tissue loss. May include undermining and tunneling
Stage IV	Full-thickness tissue loss with exposed bone, tendon, or muscle. Slough or eschar may be present on some parts of the wound bed. Often includes undermining and tunneling
Unstageable	Full-thickness tissue loss in which the base of the ulcer is covered by slough (yellow, tan, gray, green, or brown) and/or eschar (tan, brown, or black) in the wound bed

Panel grading system that is used to describe pressure ulcers.⁶⁸

Pressure relief is the mainstay of ulcer prevention and should be initiated as soon as possible once a patient is stabilized. The length of time a patient is on a spinal board is a risk factor for early pressure ulcer formation. Although randomized clinical trials have not been performed, expert opinion and observational studies endorse turning and repositioning all individuals with acute SCI every 2 hours.^{67,69} When turning a patient with SCI, it is important to avoid shear injuries. Patients should not be slid or dragged over surfaces; instead, lifts, sheets, and trapezes should be used. Pillows and foam wedges are used to pad bony prominences, and to prevent bony surfaces

from touching one another. Donut-type devices should be avoided.⁶⁷

The most vulnerable areas in SCI patients include the ischium, sacrum, coccyx, trochanters and heels. These areas should be inspected at least daily to allow for rapid detection of a forming ulcer.⁶⁷ As well, it is important to evaluate the degree of risk each patient has for the development of ulcers. The most commonly used scale for assessing this is the Braden Scale.⁶⁶

Mattresses, wheelchair cushions, commode chairs and vehicle cushions should be selected and tailored to the use of the individual patient. There is evidence that using a specialized seating clinic to make seating recommendations may help prevent ulcers from forming and should be strongly considered for all patients.⁶⁶ Even with appropriate pressure distribution surfaces, patients still need to do hourly weight shifts while using wheelchairs. Experimental evidence has shown that at least 1–2 minutes of pressure relief is needed to raise tissue oxygen levels in high-pressure areas. Although vertical lift offs for 12–30 seconds are often recommended, they are likely inadequate to relieve enough pressure.⁶⁶

If pressure ulcers become established despite optimal preventative measures, the treatment approach includes strict pressure relief, regular cleaning, adequate debridement, and the use of appropriate wound care products. The ulcer should be assessed at each dressing change and documented on a weekly basis to track healing. For stage III and IV ulcers that fail to heal, surgical treatment may be necessary with a muscle or musculocutaneous pedicle flap.⁶⁷ Of note, there are two high-quality randomized controlled trials that support the use of electrical stimulation to help wound healing in stage III and IV ulcers, and this should be considered as part of the approach to wound management.⁶⁶

Osteoporosis

Long-term Complications

Loss of bone density below the level of neurologic injury is an early and significant complication of SCI. The underlying mechanism for sublesional osteoporosis (SLOP) appears to be a combination of immobilization, lack of weight bearing and changes secondary to altered neurologic function.⁷⁰ Bone resorption and resulting hypercalciuria are evident within a few days of injury and reduced bone density is detectable on imaging by 6 weeks post-injury, before stabilizing by 1–2 years post-injury at

25–50% below average density for age-matched peers.^{71,72} Loss of bone density is associated with an increased risk of fragility fractures, particularly at the distal femur and proximal tibia.

Treatment of SLOP is targeted at both prevention of early bone loss and maintenance of bone density. For early prevention, there is some evidence of short-term efficacy with several bisphosphonates. In general, the earlier treatment is initiated after injury, the more effective it appears to be. There are fewer studies evaluating the maintenance of bone density after 1 year. As well, there is evidence that oral vitamin D may assist in the maintenance of lower extremity bone density.⁷³

There is limited evidence for the nonpharmacologic treatment of SLOP. Electrical stimulation and functional electrical stimulation (FES) cycle ergometry of at least 6 months duration may increase regional bone density over the areas stimulated. Passive standing and walking with lower extremity orthoses have been inconclusive with regard to their effects on bone density.⁷²

Heterotopic Ossification

Long-term Complications

Heterotopic ossification (HO) is the formation of abnormal bone in nonskeletal tissues. It can occur following any injury to the central nervous system including SCI.⁷⁴ Post-SCI, the incidence of HO varies across studies from 10% to 78%.⁷⁵ The most commonly affected joint is the hip, followed by the knee, with very rare involvement of other joints.⁷⁴ Consequences of HO following SCI include reduced joint mobility in 20–30% of patients and ankylosis in 3–8%.⁷⁶ Less frequent complications include decubitus ulcers, peripheral nerve entrapment, and, in rare cases, rhabdomyolysis.^{77,78}

Early HO has a nonspecific clinical presentation with local warmth, erythema, edema, limited range of motion, and low-grade fever.^{74–76} HO must be differentiated from other diagnoses such as cellulitis, septic arthritis, and deep venous thrombosis. Diagnostic imaging is important for confirming the diagnosis. A three-phase bone scan may show abnormalities as early as 2 weeks after symptom onset. While traditional radiographs are more specific, they may not show abnormalities until 3–6 weeks after symptom onset. Magnetic resonance imaging examination is the most sensitive modality, with changes present within 1–2 days of symptom onset. CT scans with 3D reconstruction may be useful for operative planning in patients with an established diagnosis.⁷⁴

Nonsteroidal anti-inflammatory drugs (NSAIDs) may reduce the development of HO when initiated within 3 weeks of SCI. There is no direct evidence that NSAIDs can treat HO once it has developed, but they are often used in this context. Etidronate has been shown to halt the progression of HO in patients with SCI in several studies.⁷⁵ Non-pharmacological management strategies include pulse low-intensity electromagnetic field therapy for prophylaxis of HO as well as radiotherapy. The role of physiotherapy has been somewhat controversial, based on a theoretical concern that aggressive passive range of motion could exacerbate ectopic bone formation. However, observational studies have shown passive and active range of motion to be safe in patients with HO.^{74,79}

Surgical excision is reserved for patients with functional impairment or secondary sequelae.⁷⁵ For most patients, surgery is planned for at least 1 year post-SCI, to allow for the ectopic bone to mature and stop growing further. Although there is no direct evidence to guide this, it is thought that recurrent HO is more likely while the ectopic bone is still metabolically active.⁷⁴

Sexual Health and Reproductive Function

Sexual function is impacted in most patients with SCI and should be addressed early following injury. A full medical assessment of the reproductive system should be made with particular attention to autonomic function, the preservation of sensation from T11-L2 and S2-S5, and the presence of anal contraction.⁸⁰

Reproductive function in men is usually affected by SCI. Erectile function, ejaculation and semen quality can all be impaired. Treatments of erectile dysfunction include PDE5 inhibitors, intracavernosal injections, and vacuum devices. Penile implants are used less often due to the potential complications, including erosion.⁸⁰ Semen retrieval methods such as vibrostimulation and electroejaculation may be used in men with SCI, but careful monitoring must be done due to the increased risk of AD.

Menstruation is often interrupted for several months post-SCI.⁸¹ However, once menses have resumed, fertility is thought to approach preinjury levels. Pregnancy in women with SCI requires increased medical oversight due to increased risk of urinary tract infections, pressure ulcers, increased immobility, decreased respiratory function and the risk of AD.⁸⁰

Mood

Long-term Complications

Depression is the most commonly studied psychological issue after SCI.⁸² Many patients experience reactive adjustment disorders following SCI, and prevalence rates of major depression can vary from 7% to 31% with suicide rates 2–6 times higher than those in the general population.^{83,84} The high prevalence of depression has a significant impact on function and quality of life. Complete injuries and medical comorbidities, including traumatic brain injury and substance use, increase the risk of depression.⁸⁵ Treatment consists of appropriate psychological support and antidepressant medications as required based on the patient's presentation.⁸⁴

Quality of Life and Community Reintegration

Long-term Complications

Quality of life is consistently reported as good or excellent in patients who are more than 5 years post-SCI.^{86,87} Interestingly, healthcare providers often underestimate the quality of life for patients living with SCI.⁸⁸ While life satisfaction is generally lower in patients with SCI during the first 2–5 years following injury, it increases in the long run.^{86,87} High functional independence, less pain, good social supports and high self-efficacy are all predictors of higher life satisfaction.⁸⁶ Increased levels of physical activity and exercise have both been linked to higher levels of physical and psychological well-being in individuals with SCI.⁸⁹

Environmental factors and social policies are also important when considering life satisfaction and community reintegration.⁸⁴ Physical accessibility in the community has improved in recent years with the introduction of curb cuts, universal design building codes and the creation of accessible public transit systems.⁹⁰ However, creating inclusive, accessible communities for people living with SCI depends on more than environmental factors. Patients need appropriate community resources including access to medical care, medical equipment and home care supports in order to achieve successful community reintegration.⁹¹

KEY POINTS

- Early referral to a specialized acute care center and integrated rehabilitation program reduces mortality, morbidity, and length of stay while improving functional outcomes.
- The mean age of patients with spinal cord injuries is increasing over time and nontraumatic spinal cord injuries are being recognized as an increasingly important cause of SCI.
- A standardized neurologic examination using the ISNCSCI is important for rehabilitation planning, for monitoring neurologic outcomes, and for predicting neurologic and functional prognosis.
- Secondary complications are an important cause of morbidity and mortality following SCI. Long-term follow-up is necessary in order to reduce the risk of rehospitalizations due to preventable secondary complications such as pressure ulcers and urinary tract infections.
- Quality of life is consistently reported as good or excellent in patients who are more than 5 years post-SCI, but health care providers often underestimate the quality of life for patients living with SCI.

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SECTION

7

Lumbar Spine 1

H Michael Mayer

Anterior and Lateral Exposures to the Lumbosacral Spine

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Snapshot

- » Clinically Relevant Regional Anatomy
- » Surgical Approaches

- » Discussion

INTRODUCTION

Anterior and lateral exposures to the lumbosacral spine are used in Anterior Lumbar Interbody Fusion procedures to gain exposure to the vertebral bodies and intervertebral disks. The three major exposure techniques are the anterior retroperitoneal, transperitoneal, and lateral transpsoas. Each approach has associated advantages, disadvantages, and specific uses. The shared goal is to gain visualization in order to perform the appropriate procedure to correct spinal pathology.

In general, the pathology helps dictate which approach may be most suitable. Pathology affecting the vertebral bodies calls for an anterior or lateral exposure, while pathology within the spinal canal is more readily managed using a posterior approach depending on the spinal level.¹ The exposure that grants the surgeon the best visualization should be strongly considered. Once an approach is selected there are other variables to consider. A left-sided approach is often selected in the lumbar spine so that the thin-walled inferior vena cava is avoided. Although the retroperitoneal technique is favored in the lumbar spine, the transperitoneal approach is also used, albeit less frequently, when the retroperitoneal approach is contraindicated. It is often used in the setting of revision surgery especially for procedures involving the L5-S1 level. Direct access to the anterior and middle columns of the lumbar spine is gained using anterior exposure techniques. There are many factors involved in selecting

the optimal approach, and this decision is typically made on a case by case basis.

CLINICALLY RELEVANT REGIONAL ANATOMY

Abdominal Wall

Regardless of the approach, detailed knowledge of the anatomy of the lumbar and sacral spine is necessary in order to decrease the risk of complications and to achieve optimal results. During the approach to the anterior lumbar spine, the outermost layers include the skin, fat, and subcutaneous tissue. The abdominal musculature consists of the transversus abdominis, and internal and external oblique muscles with contributing fascial extensions that coalesce to form the anterior and posterior rectus sheath.² These are the extrinsic muscles located adjacent to the spine along with the rectus abdominis, latissimus dorsi, and serratus dorsalis caudalis muscles (Fig. 63.1). Running ventrally and laterally the rectus abdominis muscle extends from the pubis to the costal cartilages of ribs 5–7 and the xiphoid process of the sternum. The internal and external obliques, along with the transversalis muscles, emerge from the ribs and thoracodorsal fascia and insert caudally at the iliac crest and medially at the linea alba.² The latissimus dorsi muscle originates from the sacrum, dorsal iliac crest, spinous processes of vertebra T7–L5, and the 10th–12th ribs. The serratus dorsalis caudalis muscle

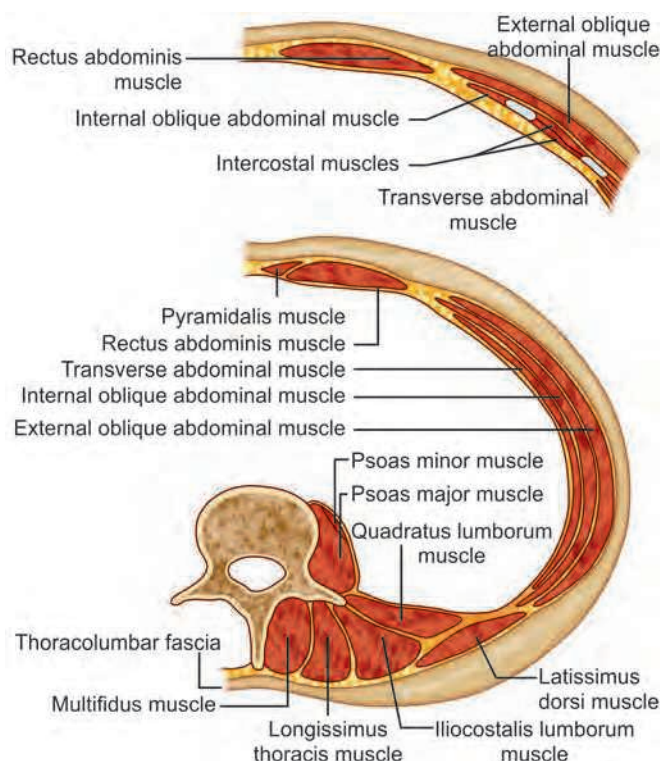


Fig. 63.1: Coronal sections through thoracoabdominal musculature above and below umbilicus.

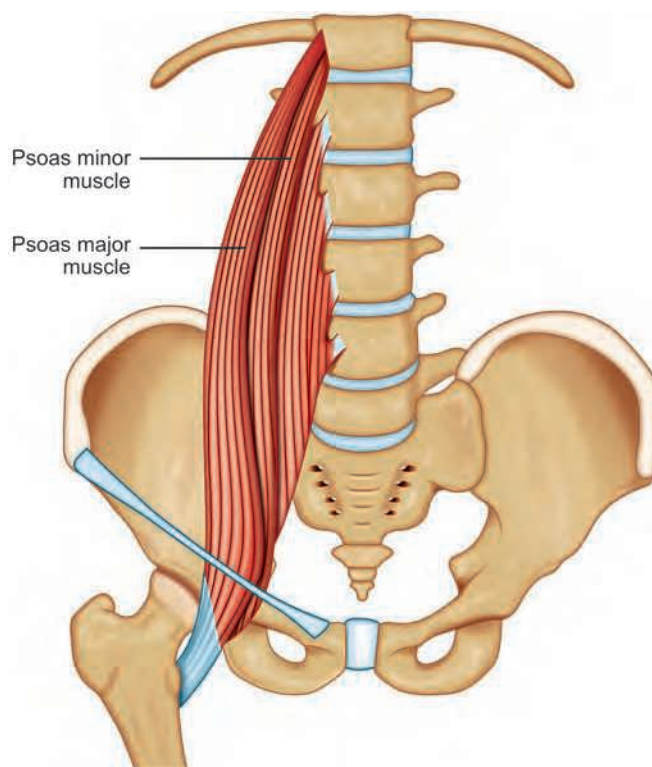


Fig. 63.2: Psoas muscle relationships to lumbar and sacral vertebrae and pelvis.

has its origin at the lower four ribs and continues on a medial course to its insertion at the thoracolumbar fascia. The intrinsic spinal muscles include the erector spinae, quadratus lumborum, multifidus, and the deep muscles.² Three muscles make up the erector spinae; these are the iliocostalis, longissimus, and spinalis muscles from lateral to medial. The psoas major muscle lays ventrolateral to the lumbar spine. Posteriorly, originating from the lateral portion of the vertebral bodies and transverse processes of L1-5, the psoas muscle continues through the pelvis and into the thigh (Fig. 63.2).² The quadratus lumborum and iliocostalis muscles are located superiorly and inferiorly in relation to the psoas muscle, respectively.⁵ The diaphragm inserts into L3 via the right crus and L2 via the left crus. The right crus must be released to access L3/4, and both must be released to expose L2/3.⁵

Vascular

The abdominal aorta begins at the level of the T12-L1 intervertebral disc at the aortic hiatus of the diaphragm and divides into the common iliac arteries around L4-5.² The location of the aortic bifurcation can vary in individuals.

The aorta is located on the left of the vena cava, which runs along the right side of the spine. The common iliac veins unite at the fifth lumbar vertebra to form the inferior vena cava.² In general, the vena cava bifurcation is superior to the L5-S1 level, and on the right side of the L5 vertebral body. The anatomy of the iliolumbar vein is of great importance to exposure of the L4/5 disc space because it can interfere with the mobilization of the iliac vessels from the anterior spine. In most cases, the iliolumbar vein branches off the common iliac vein posteriorly at the level of L5⁵ and is generally located within 2 cm of L4/5.² However, this point can vary considerably.² There is a great deal of anatomic variations in both the aortic and caval bifurcations, which can potentially complicate cases (Fig. 63.3).²

Lymphatics

The lymphatic system runs along the lateral aspect of the spine entwined with the vasculature.⁵ The association of the lymphatics with the vasculature system and the psoas muscle can lead to lymphatic vessel disruption, especially during procedures involving the exposure of levels L4/5 and higher.⁵

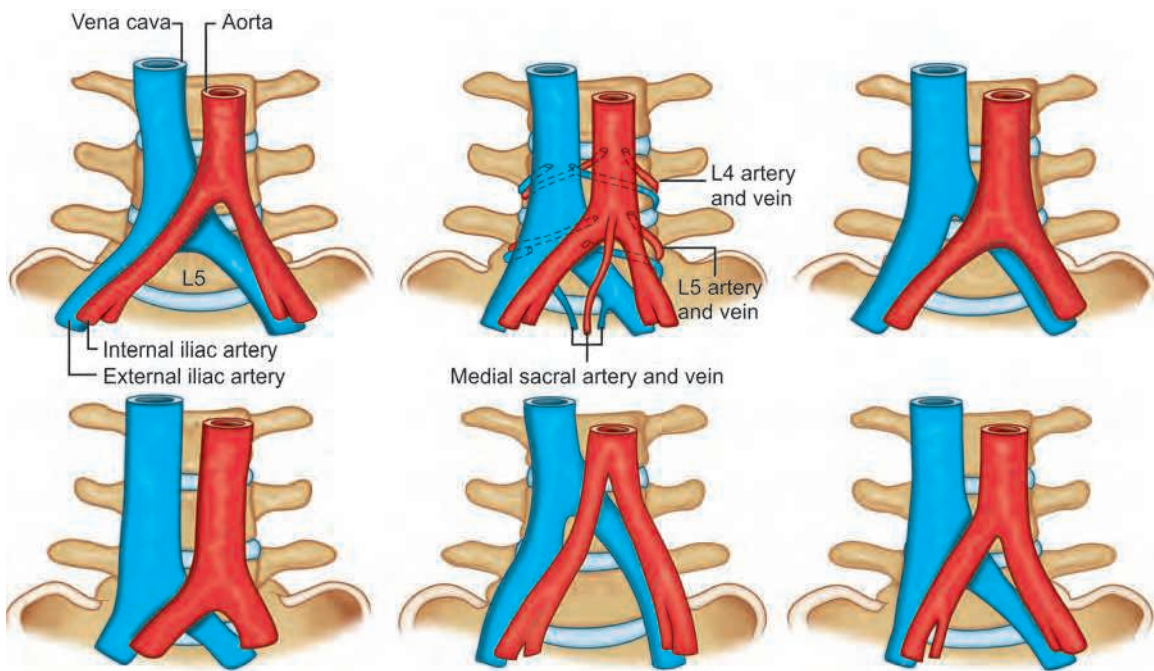


Fig. 63.3: Variations of the superior hypogastric plexus.

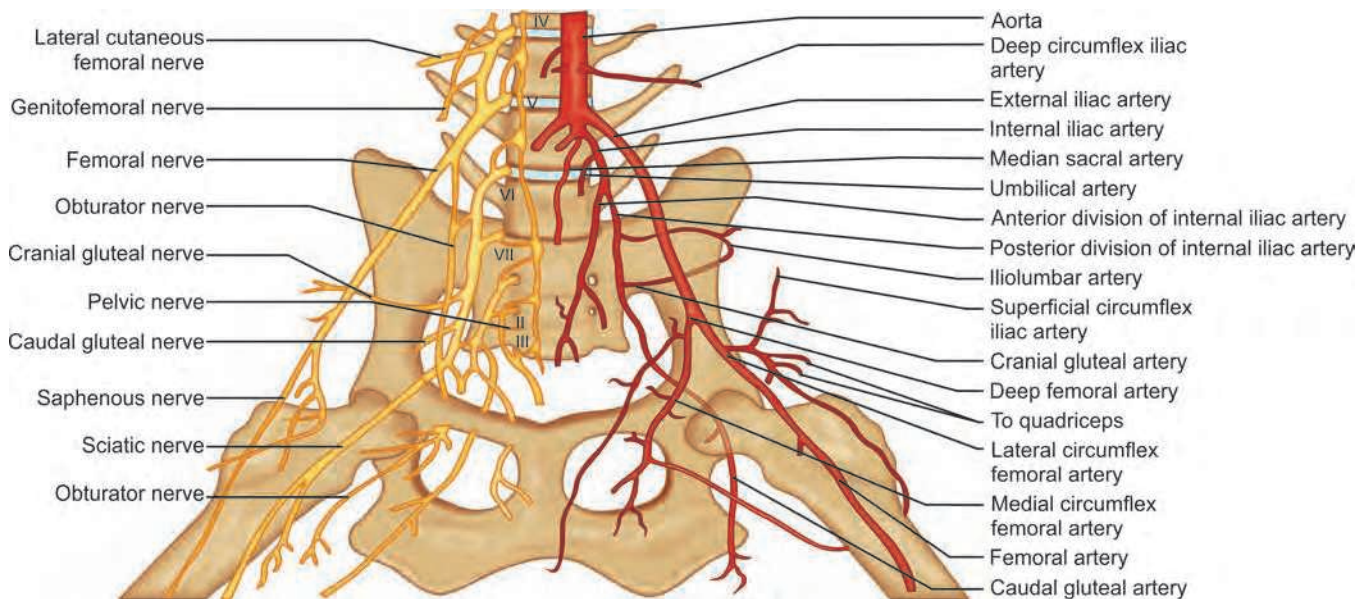


Fig. 63.4: Anatomic representation of the lumbar plexus.

Nerves

It is of great importance to possess detailed knowledge of the nerves surrounding the lumbar and sacral spine. The lumbar plexus is formed lateral to the intervertebral foramina of L1–L4, passes through the psoas muscle, and gives rise to the obturator and femoral nerves (L2, L3, and

L4).² The ilioinguinal nerve, iliohypogastric nerve, and lateral femoral cutaneous nerve course laterally to the psoas muscle.⁵ The genitofemoral nerve (L1 and L2) lies on the psoas muscle anteriorly, and the sympathetic chain lies just lateral to both the vertebral bodies and the psoas⁵ (Fig. 63.4). The sympathetic chain and parasympathetic nerves form plexuses and ganglia that run ventrally along

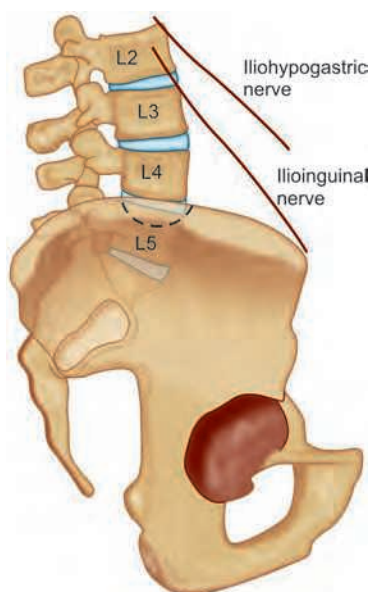


Fig. 63.5: Anatomic representation of the ilium relative to the lumbar spine.

the aorta.² Formation of the superior hypogastric plexus occurs at the level of L5 where it courses inferiorly in variable forms, ranging from a distinct nerve to a diffuse plexus.⁵ The plexus forms the right and left hypogastric nerves, which supply the pelvis with sympathetic innervation.⁵ Injury to this nerve can lead to retrograde ejaculation in men.⁵

Retroperitoneal Structures

Dorsal to the peritoneum, the kidneys lie beside the vertebral column.² The ureter is also retroperitoneal and adherent to the peritoneum. Therefore, excessive dissection should be avoided to prevent devascularization during mobilization of the ureter.

Iliac Crest

The rim of the ilium usually lies at the level of L4, although this may vary (Fig. 63.5).^{9,10} The height of the iliac crest is an important consideration for the lateral transposas approach. A high-riding iliac crest can inhibit lateral access to the L4/5 interspace limiting the success of this procedure.^{10,11}

SURGICAL APPROACHES

Considerations

The following general considerations typically apply to a given exposure. Preoperative MRI may be performed to

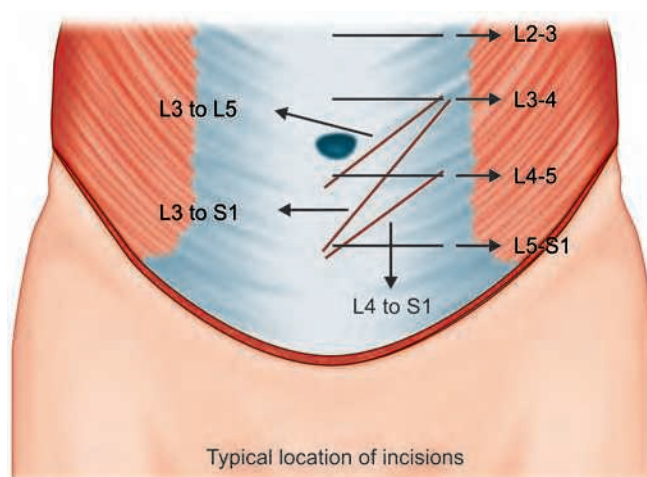


Fig. 63.6: Typical incisions through the abdominal wall.

visualize the precise location of the bifurcation of the great vessels in order to help the access surgeon plan the approach. A pulse oximeter placed on the patient's left and right first toe is useful to monitor blood flow and possible ischemia.⁴ Care should be taken to make sure that there is adequate overhead lighting, and the use of headlamps or self-illuminating retractors may be considered. The skin incision made for anterior exposures can differ based on the vertebral level, experience of the access surgeon, the number of operative levels, prior abdominal surgery, patient obesity, and the procedure being performed. Transverse incisions are used for single vertebral-level procedures, while a vertical midline incision is made for multilevel procedures where increased working space is required (Fig. 63.6).⁴ A larger vertical incision can complicate any future revision surgery due to increased interruption of retroperitoneal planes and greater scar tissue formation. If autologous bone graft is needed, it should be harvested prior to the placement of the retractors.² The use of radiolucent components such as retractors blades can be helpful owing to the number of intraoperative radiographs that must be taken to ensure correct positioning and the protection of delicate surrounding structures. A table-held retractor system is important as it exerts a constant pressure on the abdomen, increasing the space and visualization and decreasing time-consuming readjustments. Retraction time should be minimized to avoid damage to vessels.¹² In the case of a multilevel procedure, the retractors should be set up for each level and relocated for the subsequent level to minimize stretching of anterior vessels. To help reduce the chance of an ileus, gastric decompression and stool softeners are recommended.⁸

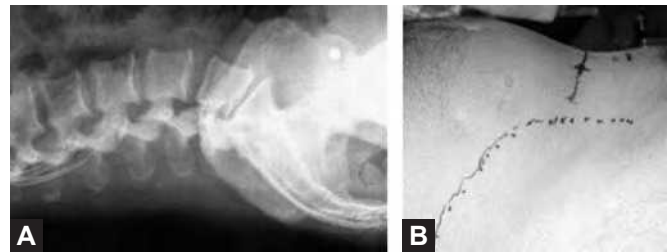
Indications and Contraindications

Procedures such as discectomy, interbody fusion, and corpectomy require access to the lumbosacral spine to treat a wide variety of conditions arising from trauma, infection, tumor, degenerative disc disease, recurrent disc herniation, spondylolisthesis, deformity, and instability. Relative contraindications for these procedures include infections of the abdomen/pelvis, severe obesity, calcifications of the aortic bifurcation, pelvic inflammatory disease, and previous anterior exposure at the same level. Procedures involving high-grade spondylolisthesis and deformities measuring $>30^\circ$ of rotation should not be performed with a transpoas approach due to limited ability for deformity correction and positioning challenges, respectively.⁶ The direct lateral transpoas approach is also contraindicated in patients who have extensive retroperitoneal scarring.⁵

Anterior

Retroperitoneal Technique

The patient is placed in a supine position. Trendelenburg positioning may help shift the abdominal contents cranially to aid the access surgeon with the exposure. The ipsilateral hip should be flexed to relax the psoas muscle. Complete muscle relaxation should be achieved by anesthesia to prevent displacement of the retractors due to muscle tension during the procedure.⁴ The level of the incision may be assessed with lateral fluoroscopy, which can provide clues as to which angle will provide the best visualization (Figs. 63.7A and B). Approach from the left side is preferable for avoiding the liver and inferior vena cava, whereas the thicker walled aorta is retracted instead.² The incision is made in a lateral orientation starting between anatomical landmarks of the umbilicus and the pubic symphysis.³ Next, electrocautery is used to carefully dissect the subcutaneous tissue, fascia, and muscles until the retroperitoneal space has been accessed (Fig. 63.8). The exposure proceeds in-line with the skin incision, and the external oblique, internal oblique, transversus abdominis, and transversalis fascia are split in succession until they have been divided (Fig. 63.9).³ While dissecting the left rectus muscle, attention must be paid to preserving the superficial epigastric vessels. The peritoneum is carefully reflected anteriorly by blunt dissection with a finger along the inferior edge of the posterior rectus sheath to gain access to the retroperitoneal space (Fig. 63.10). The ureter and retroperitoneal fat are also reflected anteriorly. The next step is to palpate the vertebral bodies and safely move



Figs. 63.7A and B: Use of fluoroscopy in the retroperitoneal approach (A) in positioning of lateral skin incision (B).

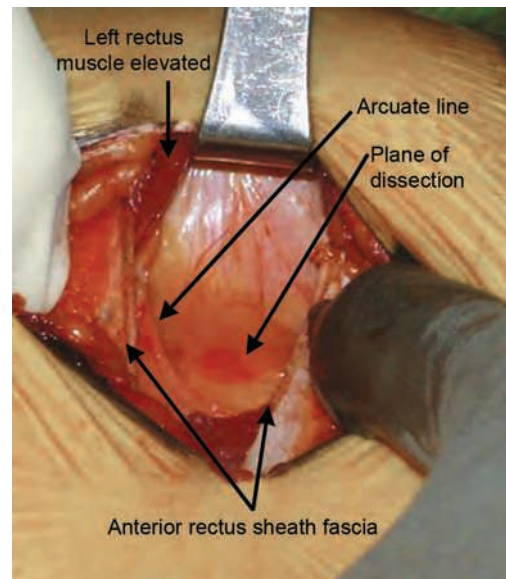


Fig. 63.8: Dissection exposure to access the retroperitoneal space.

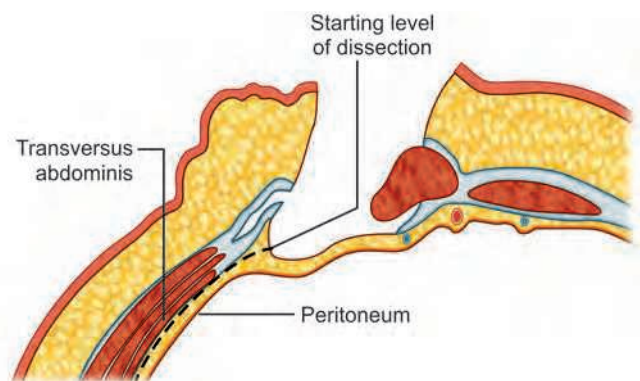


Fig. 63.9: Axial view of the starting level of dissection.

the great vessels anterior to the spine and out of the field using a Deaver retractor. At approximately the L4 level the common iliac arteries and veins bifurcate and must be retracted carefully to expose the anterior portion of

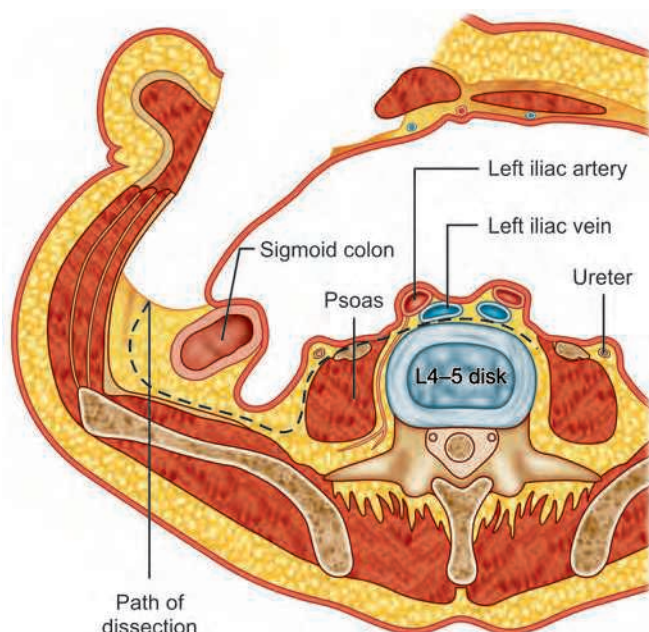


Fig. 63.10: Axial view of the appropriate retroperitoneal plane of dissection to the lumbosacral spine.

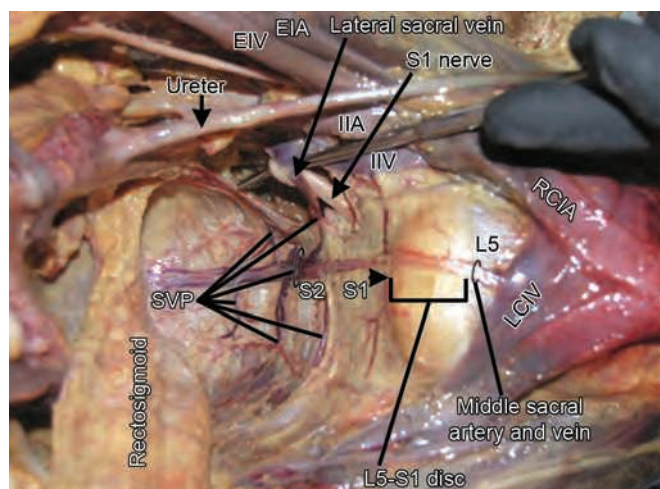


Fig. 63.12: Sacral vessels overlying L5 vertebral body.

the vertebral bodies.⁶ When approaching the L4/5 level, it is important to ligate and transect the iliolumbar vein to reduce the risk of injury to this vessel. Care must be taken to avoid violation of the lumbosacral plexus lying in close proximity to the iliolumbar vein. The landmark for the lumbosacral region is the sacral promontory, which is found just below the aortic bifurcation (Fig. 63.11). The vasculature overlying the L5 vertebral body includes the common iliac artery and vein anteriorly, the internal iliac

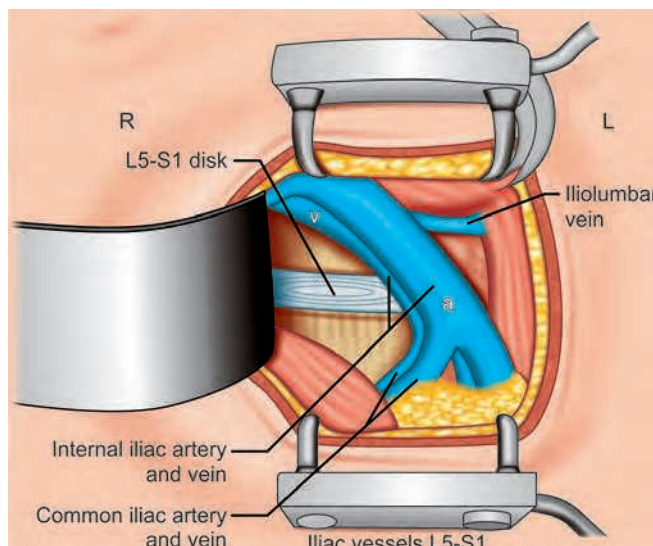


Fig. 63.11: Vasculature overlying the L5 vertebral body.

artery and vein just posterior, and the iliolumbar vein most posterior (Figs. 63.4 and 63.12). These vessels must be retracted gently to achieve exposure of the vertebral body and intervertebral disks. The external iliac artery should be mobilized distally in order to reduce longitudinal stress on the vessel and thereby decrease the risk of thrombosis.³ Using a Kittner dissector, the appropriate disc space can be mobilized and the middle sacral vessels ligated.⁴ The exposure should now yield an open visual field to the anterior portion of the lumbar spine sufficient for managing the affected pathology.

Transperitoneal Technique

Antibiotics should be administered preoperatively, and bowel preparation is often given the day before the surgical procedure.⁴ The patient is placed in the supine position with the sacrum elevated. Adjusting the operating table into the Trendelenburg position shifts the abdominal contents toward the upper abdomen. Two incisions are possible, midline and a transverse, and fluoroscopy may be used to aid in the selection of the incision site.³ If using a midline incision, start inferior to the umbilicus; however, this incision can be extended proximally, if necessary, avoiding the umbilicus. The patient may prefer the transverse incision for cosmetic reasons. Proceeding with the transverse incision, the rectus sheath must be transected and the rectus abdominis muscle divided.³ Joined together are the posterior rectus sheath, abdominal fascia, and peritoneum. By opening both the rectus

sheath and abdominal fascia, the posterior peritoneum may be incised. As a result, access is granted into the peritoneum. Progressing through the peritoneum should be done carefully as to not disrupt any segment of fragile bowel.⁶ The abdominal contents are retracted rostrally while proceeding deeper. The sacral promontory may now be palpated as an anatomical landmark for the aortic bifurcation just superior to it. The underlying tissue may be coated with a layer of saline solution at this point in order to make identification of smaller structures easier. The common iliac artery may be retracted proximal to the bifurcation to augment the exposure.² Next, the middle sacral artery and hypogastric plexus must be retracted laterally. If the left common iliac vein limits access to the L5-S1 region, it must be carefully mobilized before addressing the spinal pathology (*see* Fig. 63.10). It is best to perform longitudinal blunt dissection in this region to mobilize the smaller vessels. If bleeding occurs, monopolar electrocautery is ill advised due to possible damage to the hypogastric plexus; instead, a sponge and direct finger pressure should be applied followed by suture ligation or bipolar cauterization.⁴ Once the vasculature anterior to the vertebral body has been appropriately managed, the pathology can be corrected. After completion of the surgical procedure, the posterior peritoneum is closed using absorbable sutures and the abdominal contents are returned. The bowel and omentum are then replaced, and the rectus, subcutaneous tissue, and skin are closed in multiple layers.

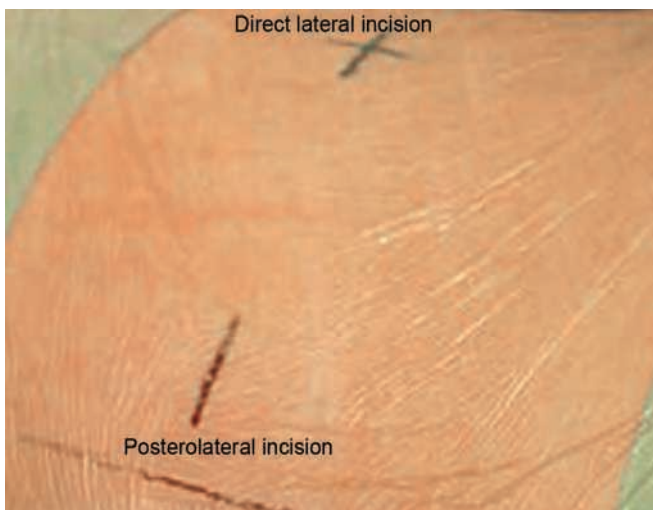


Fig. 63.13: Skin incisions in the transpsoas approach.

Lateral

The current technique most commonly used in the United States to access the lateral aspect of the lumbosacral spine is the minimally invasive lateral transpsoas approach, first described as the Extreme Lateral Interbody Fusion by Ozgur et al.⁵ The uses for this approach include, but are not limited to, lumbar fusion to treat low-grade spondylolisthesis, and adult degenerative lumbar scoliosis.⁶ This approach preserves both the anterior and posterior longitudinal ligaments. The lateral approach is used by some surgeons to treat older patients on the basis of involving significantly less visceral and vascular dissection for exposure. Unlike the previous two approaches described, the anesthesia administered should not include a muscle relaxant or paralytic agent beyond the initial intubation because muscle twitch is required for electromyogram (EMG) testing of the psoas muscle during the insertion of dilators.³

Transpsoas Technique

An early description of a minimally invasive lateral approach included two incisions, a direct lateral incision in the flank over the intervertebral disc and a posterolateral incision just lateral to the paraspinal muscles (Fig. 63.13). The patient is placed in the lateral decubitus position under general endotracheal anesthesia (Fig. 63.14). The patient should be secured in place for the procedure with pillows supporting the midsection to increase the width between the 12th rib and the anterior superior iliac crest,

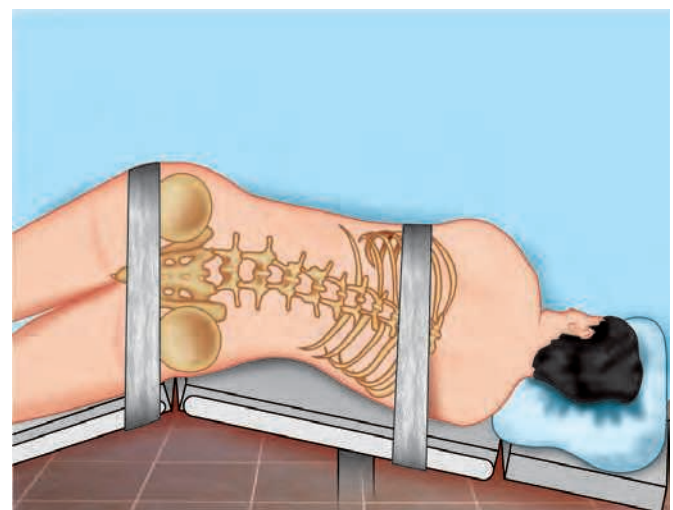


Fig. 63.14: Lateral decubitus patient positioning.

thus creating a larger window for exposure.¹⁴ The top leg should be flexed so that the psoas muscle is relaxed. In approaching the L2/3 disc space, the 12th rib may need to be resected. For exposing the L1/2 disc, an intercostal approach between the 11th and 12th ribs is utilized. The ideal incision site can be determined using fluoroscopy and marked on the skin accordingly (Fig. 63.15). A second incision is made posterior to the first, which will facilitate blunt dissection between the erector spinae and the oblique musculature (Fig. 63.16). With an index finger, the surgeon can feel through the posterolateral muscle down to the lumbodorsal fascia, which is opened with little resistance to access the retroperitoneal space. Next, the surgeon orients his or her finger superficially toward the incision

site to open a working channel for the dilator trajectory.¹⁴ Using an index finger, the surgeon guides the dilators through the direct lateral incision down to the surface of the psoas (Figs. 63.17A to D). Electromyogram monitoring is used while the psoas muscle is carefully divided to help prevent damage to the lumbar plexus contained within the psoas muscle. The psoas fibers are gently divided taking care not to damage the lumbar plexus or genitofemoral nerve.⁵ The initial dilator is secured using a Kirschner wire passed through the dilator and into the disc space, which is subsequently followed by larger dilators to gradually increase the opening. Once the psoas has been divided, the dilators should be at the level of the vertebral body. The expandable retractor is then placed over the dilators



Fig. 63.15: Use of fluoroscopy to aid in exposure of the L1/2 disc in the transpsoas approach.

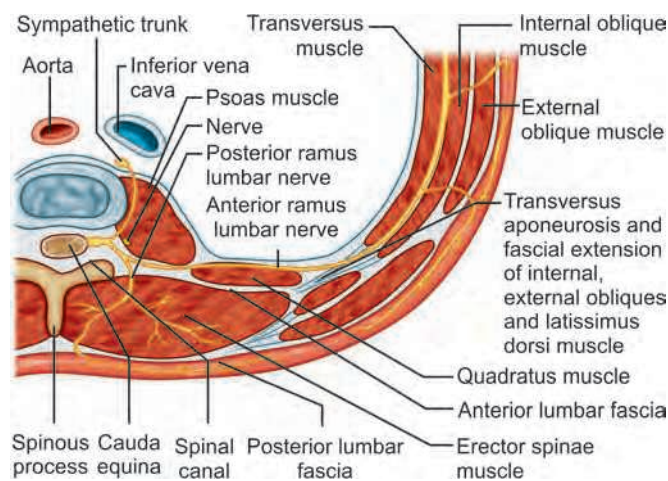
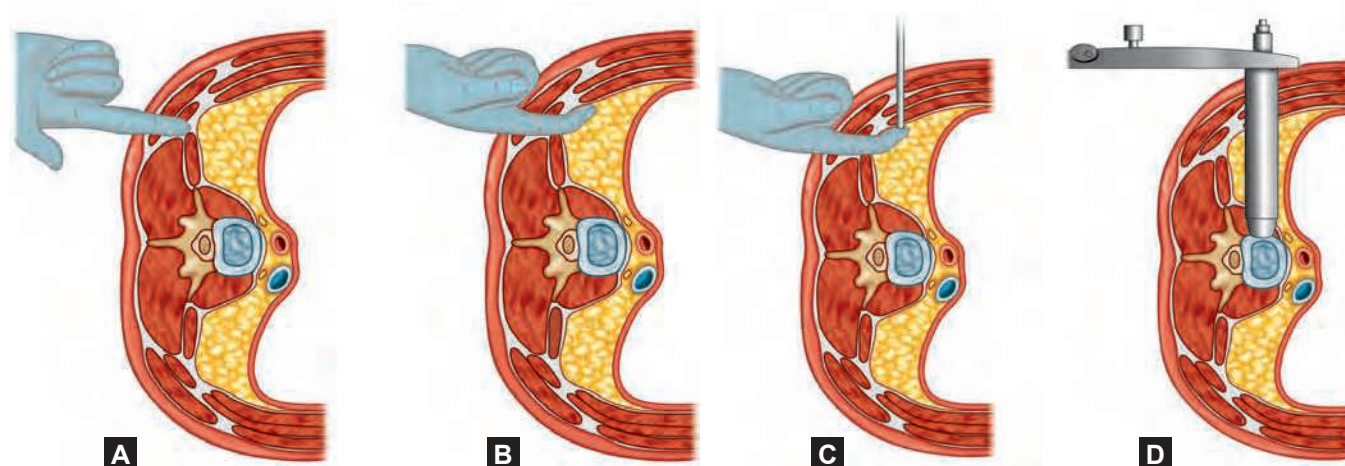


Fig. 63.16: Axial view of the plane of dissection between the erector spinae and the oblique musculature.



Figs. 63.17A to D: Using an index finger, the surgeon guides the dilator through the direct lateral incision down to the surface of the psoas.

and locked in place to the surgical table. The dilators are removed to access the disc space, and a lateral radiograph may be taken to confirm positioning. The exposure is complete and the remainder of the procedure may be performed.

Complications

There is potential for a wide variety of complications with anterior lumbar exposures. The retroperitoneal and transperitoneal approaches have similar complication profiles. Awareness of prior surgical procedures or disease processes of the lower abdomen is vital as this can make manipulating tissue planes more challenging. Some testicular pain postoperatively has been reported in male patients with past hernia repairs.⁵ During the dissection and mobilization stages, minimizing force can help protect structures such as the ureter.⁵ Mobilizing the gonadal vessels and the left ureter *en bloc* with the peritoneum also can help protect the ureter.⁵ Tears in the peritoneum can occur, and primary repair is encouraged to decrease the potential of intestinal injury.⁵ In the case of an injury leading to the exposure of luminal contents, the surgeon should consider deferring spinal intervention until healed.⁵ A frequently encountered difficulty is the retraction of the great vessels anterior to the spinal column, especially at the L4/5 level. The variable location of the iliolumbar vein places this vessel at risk for avulsion during an L4/5 exposure, and this can cause a significant venous bleed.⁵ Vessels can sustain injury during retraction or from manual mobilization. Increased retraction time increases the risk of damage to blood vessels. Because of the location of the great vessels anterior to the lumbar spine, ligation of the inferior vena cava and common iliac veins above and below the lesion can be performed quickly as a last resort if bleeding cannot be otherwise controlled in order to prevent catastrophic morbidity and mortality. The risk for thromboembolic events may be increased in patients with baseline atherosclerosis.⁵ Injuries to the lymphatic system can occur, but typically are not significant. In the rare event of a lymphocele, percutaneous drainage is recommended.⁵ Infectious complications are rare, but when they occur they should be treated with antibiotics and drainage.⁵ Deep space infections are also rare, occurring in <1% of patients.¹² One of the most feared complications is injury to the hypogastric nerve, which may lead to retrograde ejaculation in men.⁵ The use of electrocautery should be minimized in the anterior lumbar region due to an increased risk of damage to the superior hypogastric plexus.

It has been documented that the autonomic plexus is vulnerable to injury due to increased heat, and the resulting lesion can also cause retrograde ejaculation.⁷ Both retroperitoneal and transperitoneal approaches can result in hypogastric plexus damage; however, it has been reported that there is a 10-fold increase in the incidence of retrograde ejaculation with a transperitoneal approach.¹³ This complication may be avoided with careful dissection practices.

Complications secondary to the minimally invasive lateral approach, a relatively new procedure, have been reported but the literature is still developing in this regard. To minimize risk of complications such as numbness of the lateral thigh, minimal retraction is used.¹ It is important to have clear images on fluoroscopy for the transpoas approach, and intraoperative radiographs should be taken frequently to make sure the correct alignment is being maintained.⁵ When the exposed area has not been properly irrigated, artifacts may affect intraoperative fluoroscopy. Although this approach effectively provides access to spinal levels from T7 to L4-L5, it may be difficult to reach L4/5 with a high-riding iliac crest, and current technology does not allow this approach to treat spinal disease at L5-S1.¹

DISCUSSION

There are various approaches to choose from for exposing the lumbosacral spine. Selecting one requires careful review of the strengths and potential risks of each approach as well as the intricacies of the case. An anterior exposure is best suited for situations where broad visualization of the lumbar spine is required. The retroperitoneal approach can probably be considered the gold standard because of a lower complication rate, decreased damage to viscera and great vessels, broad exposure, and less abdominal wall tissue dissection. Although the transperitoneal approach may be simpler for exposure of the L5-S1 disc space, it is not commonly used because of the associated complication profile. There is a higher complication rate than with the retroperitoneal approach,⁵ and most notably there is an increased risk of hypogastric plexus damage that can lead to retrograde ejaculation.⁵ Therefore, this approach should not be utilized for young male patients when possible and used mainly for revision surgeries or in patients with preexisting retroperitoneal scarring from prior surgery or radiation.⁵

The minimally invasive direct lateral transpoas approach can provide excellent exposure to the lumbar spine, and some authors have described a favorable complication

profile compared with traditional open techniques. When compared with the anterior approaches described, there is decreased dissection and damage to surrounding tissues, less risk of damage to the great vessels and viscera, reduced blood loss, lower operative time, and no need for an access surgeon. Whereas a large body habitus can be problematic in other approaches, this approach places the patient in a lateral decubitus position, which mobilizes the abdomen away from the spine thereby aiding in opening the retroperitoneal space.¹⁴ However, significant limitations include the inability to access the L4/5 disc space in the case of a high-riding iliac crest, the inability to access L5/S1, and complications related to lumbar plexus injury, including postoperative sensory and motor deficits.¹⁴

CONCLUSION

In some cases, spinal pathology and the location thereof will dictate the best surgical approach, although the experience and approach of the surgeon are also critical elements. The anterior transperitoneal approach should be used mainly for revision surgery or with extensive prior retroperitoneal surgery. In the lower lumbar region, if the spinal disease can be attended to unilaterally, the retroperitoneal approach is preferred.¹ The lateral transpsoas approach cannot be used below the L4-L5 level due to obstruction by the iliac crest, and many surgeons avoid the use of this approach at the L4-L5 level because of descriptions of increased neurologic complication rate at this spinal level.

Anterior Exposure

Retroperitoneal Approach

Advantages

- Lower complication rate
- Decreased risk to viscera and great vessels compared with transperitoneal approach
- Better cosmesis
- Less abdominal wall tissue dissection
- Broad exposure to lumbar spine.

Disadvantages

- May be more difficult with retroperitoneal scarring from infection, radiation, or prior surgery.

Transperitoneal Approach

Advantage

- Easily visualizes the L5-S1 disc space.

Disadvantages

- Used less often, and therefore less surgeon experience
- Requires manipulation of peritoneal contents
- Increased risk of injury to the sympathetic chain and hypogastric plexus
- Higher complication rate
- Reserved mainly for revision surgeries or with pre-existing retroperitoneal damage.

Lateral Exposure

Lateral Transpsoas Approach

Advantages

- Access surgeon is often not required
- Less dissection and damage to abdominal structures
- Decreased need to retract the peritoneum and great vessels

Disadvantages

- Anatomical barriers at iliac crest inferiorly preclude access to L5-S1
- Careful EMG monitoring of the psoas muscle required to prevent injury during dissection and to prevent injury to the lumbosacral plexus
- Exposure to intraoperative fluoroscopy
- Decreased deficit correction compared with other techniques.

KEY POINTS

- Pathology dictates which approach (anterior vs lateral) and which exposure (open vs laparoscopic) are utilized.
- The anterior retroperitoneal approach is the standard, due to decreased complication rate, better cosmesis, and less abdominal wall dissection in providing exposure to the lumbar spine relative to the transperitoneal approach.
- Plan preoperatively and review the specifics of the case and the approach with the access surgeon. Providing an adequate exposure safely and efficiently, while avoiding overdissection and maintaining a safe retraction, is paramount.
- Lateral interbody fusion is a procedure used for the correction of degenerative scoliosis, multilevel fusions, or adjacent segment degeneration. This can be performed in a minimally invasive fashion that does not require anterior access and may shorten recovery time.
- The lateral approach to the spine requires splitting the psoas muscle, and neurologic monitoring is

required to decrease the risk of nerve injury. Because of the smaller incision and decreased tissue dissection, there is a greater reliance on imaging and exposure to radiation from fluoroscopy.

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Posterior Approaches to the Lumbosacral Spine

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Snapshot

- » Significance of Musculotendinous Anatomy of the Lumbosacral Spine
- » Significance of Neuroskeletal Anatomy of the Lumbosacral Spine
- » Posterior Lumbar Instrumentation Procedures
- » Minimally Invasive Lumbosacral Surgery

INTRODUCTION

Posterior approaches to the lumbosacral spine are relevant for surgical treatment of many spinal pathologies, including traumatic, degenerative, vascular, congenital, and neoplastic disorders. Posterior techniques are not only the most common surgical exposure of the lumbosacral spine but are also fundamental techniques for most spinal surgeons. Posterior approaches can be classified into either midline or paraspinal approaches, referring to the laterality of the surgical approach, in combination with a macrosurgical and/or a microsurgical exposure.¹ Some examples of macro- and microsurgical midline posterior approaches to the lumbosacral spine include laminotomy, laminectomy, medial and lateral facetectomy, pedicle subtraction osteotomy, Smith-Petersen osteotomy, and en bloc spondylectomy.²⁻⁹ Using a historical perspective, this chapter briefly reviews the concepts of conventional and minimally invasive posterior lumbosacral approaches with regard to macro- and microsurgical exposures, and the progression of surgical methods from rigid fusion to dynamic stabilization in combination with the development of minimally invasive spinal surgery (MISS).

SIGNIFICANCE OF MUSCULOTENDINOUS ANATOMY OF THE LUMBOSACRAL SPINE

Conventional midline approaches to the spine are relatively straightforward and require relatively little anatomical

consideration. They allow direct access to all lumbosacral levels. However, midline macrosurgical exposures carry with them serious limitations including sacrificing or compromising of major stabilizing elements of the posterior spine, especially of the three major muscles: multifidus, longissimus, and iliocostalis (Fig. 64.1).^{10,11} Among them, the multifidus muscle is especially relevant because it has a fundamental function as a spinal stabilizer and has a unique architecture.¹¹⁻¹⁷ For instance, Macintosh et al¹⁵ described that only the multifidus muscle is present in the region of the L5 vertebra, which is covered by the erector spinae aponeurosis but not the actual muscle. Bojadsen et al.¹⁸ supported the absence of other muscle fibers in the back of L5-S1 and indicated that the multifidus represents most of the muscle fibers present on the back of the lumbosacral transition. The very high physiological cross-sectional area of the multifidus relative to other muscles of the lumbar spine, in addition to the muscle's relatively short fibers, indicates that the multifidus muscle is architecturally designed to produce large forces over a narrow range of lengths.¹¹

Muscular instability in the lumbosacral region, whether as a cause of, or as a result of, spinal disorders, has been considered an important problem in spinal surgery and has led to ever-increasing interest in MISS. Paradoxically, classic posterior approaches that disrupt the multifidus and other erector muscles have historically been widely applied, in spite of established evidence that pathological changes of these muscles are associated with various

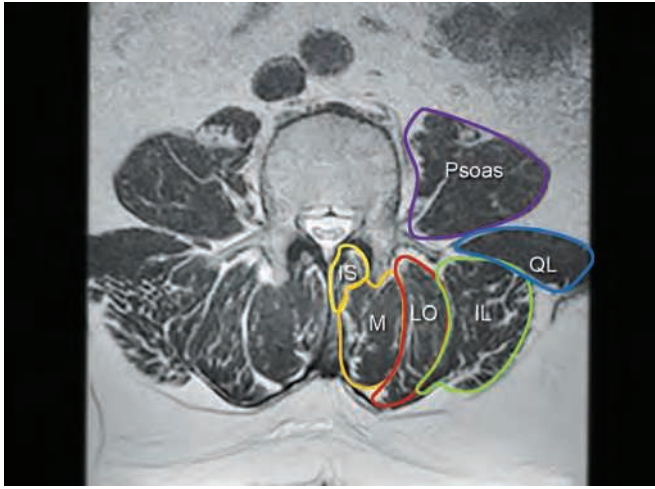


Fig. 64.1: Cross-sectional MRI image on L4 level showing the interspinalis (IS), multifidus (M), longissimus (LO), iliocostalis (IL), quadratus lumborum (QL), and psoas muscles.

degenerative spinal diseases.^{11,19,20} Taking into consideration the relationship between muscle injury and degenerative spinal disorders, conventional midline posterior approaches may thus be regarded as a cause of iatrogenic muscle damage.

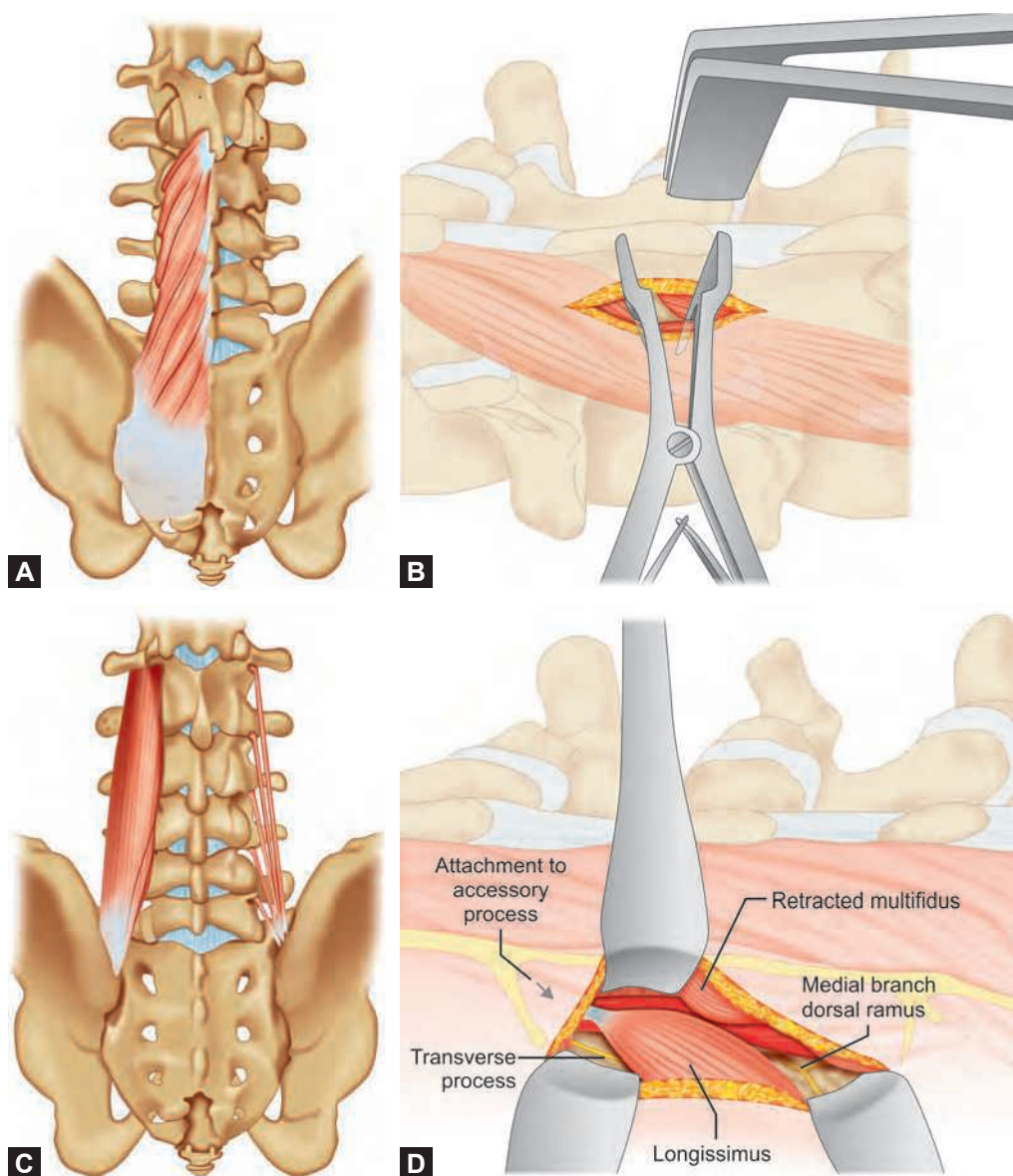
Other risks to the muscles of the lumbosacral spine include denervation and devascularization, which are often unavoidable when wide operative fields are needed and when surgery is performed with a retractor engaged to the lumbosacral spinal muscles. The risk for musculotendinous injury is highest when forceful muscle retraction is performed to achieve wide operative fields for far-lateral discectomy, posterolateral fusion, or manipulation of anterior spinal elements, especially during cases of inadequate midline exposure.^{10,12,21-25}

For the purpose of reducing musculotendinous injury and for preservation of neurovascular supply to back muscles in the posterior approach, anatomical considerations are as important as the details of the surgical technique. For instance, when using a posterior midline macroscopic exposure, accurate dissection of periosteal planes from posterior spinal bony elements, or the so-called subperiosteal dissection, is crucial. Unnecessary dissection of muscles attached to irrelevant parts of bones or joint capsules, excessive use of electrocautery, and excessive and prolonged muscle traction, should all be avoided.¹³ The removal of bony tissue, including spinous, transverse, and articular processes, should not be performed unless necessitated because they comprise the crucial biomechanical framework onto which the back muscles

attach.^{14,24,26} When using a posterior paraspinal exposure, which is usually performed for percutaneous pedicle screw placement or tubular retractor-guided microscopic surgeries, muscle-splitting techniques that involve separation of muscles by index finger dissection can be used to avoid muscle damage.²⁷ One such technique is intramuscular splitting, which uses finger dissection through the multifidus muscle to access the laminae and facet joints (Figs. 64.2A and B).²⁸ Currently, most tubular retractor-guided procedures, including removal of paramedian disc herniation, removal of contralateral intraforaminal disc herniation, unilateral laminotomy for bilateral decompression, and minimally invasive transforaminal lumbar interbody fusion (MIS TLIF), are performed using the intramuscular splitting technique.²⁹⁻³³ Another muscle splitting technique, the intermuscular splitting or cleaving technique, involves finger dissection along the cleavage plane between the multifidus and the longissimus thoracis muscles (Figs. 64.2C and D). Intermuscular splitting between the multifidus and the longissimus thoracis is appropriate for situations requiring percutaneous pedicle screw placement at L1-2 or extraforaminal exposure for removal of far-lateral disc herniation between the L2-5 levels, and is a tried and proven approach since its first description in 1958 by Wiltse as the sacrospinalis splitting method.³⁴⁻³⁸ Dissection between longissimus and iliocostalis lumborum provides for a less invasive access to the pedicle for screw placement in the lumbosacral junction, especially in L3-S2, or for extraforaminal exposure for removal of far-lateral disc herniations at the L4-S1 levels compared with dissecting near or within the multifidus. This is because the iliocostalis is free from attachment to the erector spinae aponeurosis, whereas the multifidus lumborum fans as downward and laterally to attach to the ilium under the longissimus, thereby obstructing the surgical field (Table 64.1).³⁹ Recent evidence strongly suggests that the paraspinal muscle-splitting techniques can reduce back muscle injuries and facilitate access to surgical targets and can provide enough room for changing trajectories by moving the screw guides or the tubular retractors, should the need arise.^{17,24}

SIGNIFICANCE OF NEUROSKELETAL ANATOMY OF THE LUMBOSACRAL SPINE

Understanding the neural structures in correlation with the skeletal structures is crucial for macro- and microsurgical



Figs. 64.2A to D: Illustration showing intramuscular approach through the multifidus (A and B) and intermuscular approach between multifidus and longissimus (C and D).

posterior approaches to the lumbosacral spine. McCulloch and Young⁴⁰ described the neuroskeletal anatomy on the lumbosacral region using a “three-storied house” concept demonstrated here using schematic diagrams (Fig. 64.3). The spinal canal was divided into central canal and lateral zones. The lateral zone includes the lateral recess, intra- and extraforaminal areas. Most acquired central spinal canal stenosis develops in the first story, with some extension of the lesion into contiguous parts of the second story of the same level and the third story of the

adjacent inferior level. Pathologies involving subarticular stenosis, including lateral recess stenosis and central stenosis, could be decompressed bilaterally through a unilateral interlaminar window.⁴⁰

Laminectomy/Facetectomy

Unilateral laminectomy in the lumbar and sacral spine was first performed by Taylor⁶ on a cadaver in 1908. In 1977, Wiltse⁹ first published the surgical procedure of laminectomy on a human patient, referring to the removal

Table 64.1: Summary of tubular retractor guided approaches to the posterior lumbosacral spine.*Tubular retractor-guided MISS approaches*

Approaches	Ipsilateral	Contralateral
Intramuscular (multifidus)	Paramedian HLD on L2-S1 TLIF on L2-S1 lateral recess stenosis on L2-S1	Bilateral decompression through unilateral approach: Central stenosis L2-S1 Intraforaminal stenosis L2-S1 Intraforaminal HLD L2-S1 Lateral recess stenosis L2-S1
Intermuscular	Between multifidus and longissimus	Percutaneous screws L1-2 Far-lateral HLD L2-5 Intraforaminal stenosis L2-5 Extraforaminal stenosis L2-5
	Between longissimus and iliocostalis	Percutaneous screws L3-S2 Far-lateral HLD L4-S1 Extraforaminal stenosis on L4-S1

(MISS: Minimally invasive spinal surgery; L: Lumbar; S: Sacrum; HLD: Herniated lumbar disc; TLIF: Transforaminal lumbar interbody fusion).

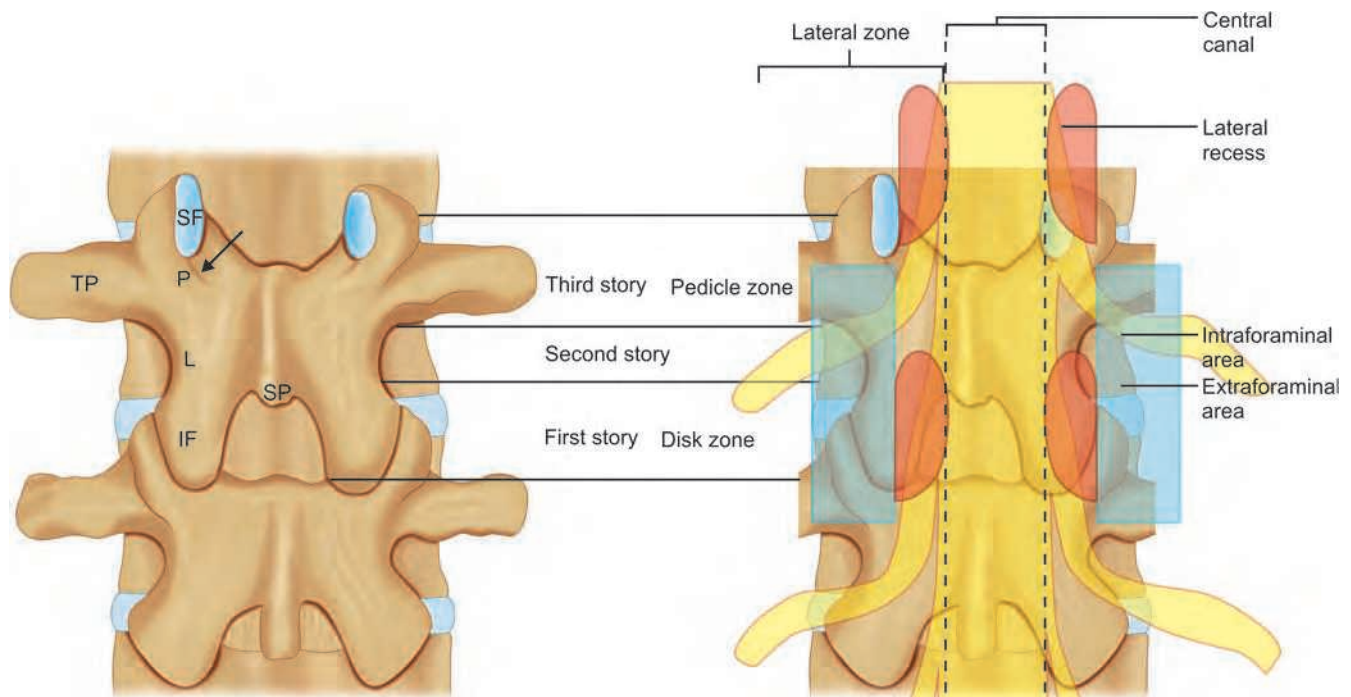


Fig. 64.3: Illustration representing the “Three-Storied House” concept. The grids show the first, second, and third stories and the divisions of lateral zone. Each story has two posterior elements. The isthmus (P) divides the posterior element into three superior elements and three inferior elements. (SF: Superior facet; IF: Inferior facet; L: Lamina; P: Pars; TP: Transverse process; SP: Spinous process).

Source: Modified with permission from the drawing of McCulloch and Young. *Essentials of Microsurgery* by McCulloch and Young. Philadelphia: Lippincott-Raven, 1993

of all bone between the base of the spinous process and approximately 1 cm medial to the facet joints with sparing of the pars interarticularis. If a bilateral laminectomy

is performed, laminae on both sides of the spinal processes, including the spinal process itself, are removed (Fig. 64.4). If laminectomy and facetectomy are performed

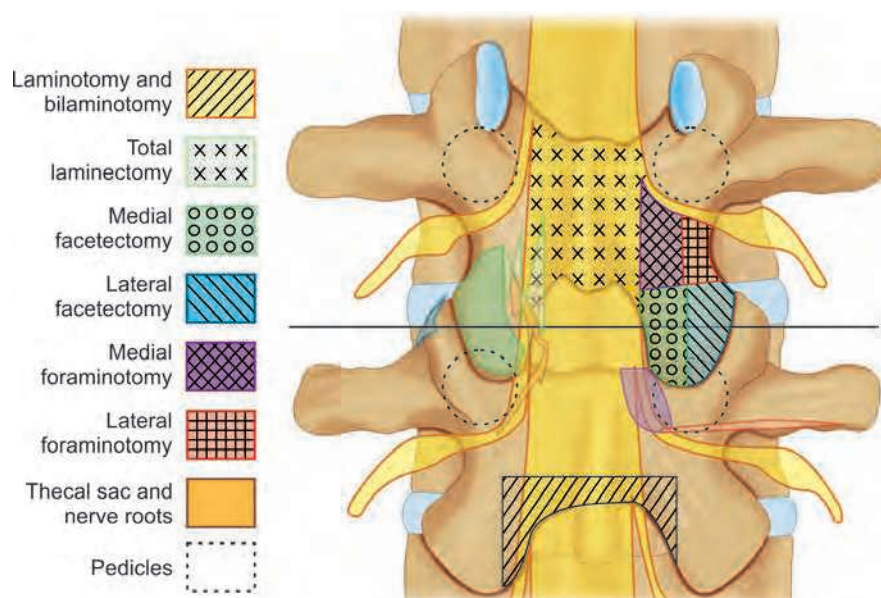


Fig. 64.4: Illustrations show laminotomy, bilaminotomy, laminectomy, total laminectomy, medial and lateral facetectomy, and foraminotomy.

concurrently, one lamina is removed from the base of the spinous process and outward to include the ipsilateral inferior articular process, pars, and a portion of the superior articular process of the vertebra below. The amount of bone removed in laminectomy and facetectomy results in a complete unilateral decompression, completely deroofing both the exiting and traversing spinal nerve roots through a single-level procedure.⁹

Theoretically, even if a laminectomy procedure included a partial removal of the pars and facet joints medially, stability should not be seriously compromised.⁹ However, over-removal of the pars and medial facets can increase the risk for instability. Total laminectomy may thus increase or cause vertebral instability unless fusion is performed.⁴¹⁻⁴³ These observations have led to the development and adoption of surgical techniques, which preserve sections of the posterior osteoligamentous arches, such as multiple laminotomy.⁴⁴

Laminotomy/Bilaminotomy

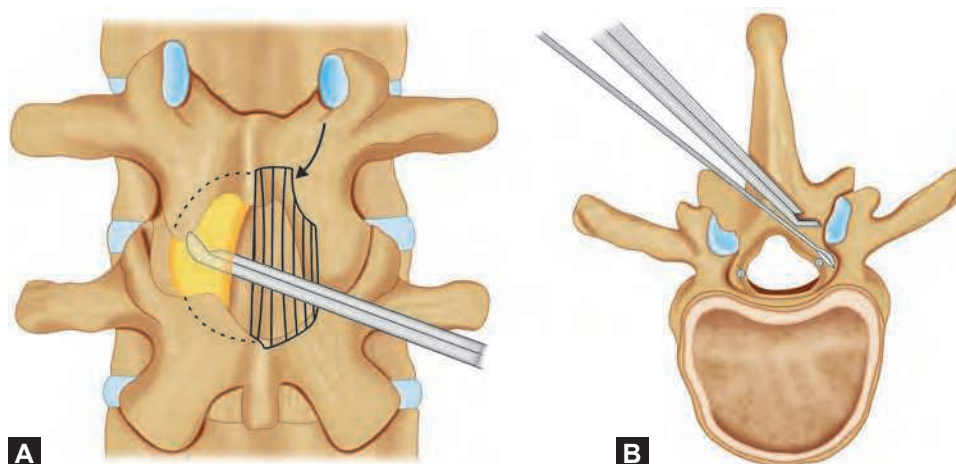
Laminotomy refers to the removal of an inferior portion of one lamina without involving the superior portion of the lamina, inferior articular processes, and, especially, the facet joints. This procedure can more correctly be called bilaminotomy as it is common practice for unilateral adjacent upper and lower laminae to be cut through in order to reveal the spinal canal (Fig. 64.4). Bilaminotomy is

performed for procedures such as spinal decompression and discectomy as it allows for thorough access to the spinal canal without creating excessive biomechanical instability, since the amount of vertebral material removed is minimal.^{9,36} With respect to the preservation of vertebral stability, multiple laminotomy has a great advantage over total laminectomy because the latter involves a much more extensive removal of stabilizing structures.⁴⁴⁻⁴⁶

Conventional Foraminotomy

Central constriction (spinal canal stenosis) is most commonly caused by pathology of the medial part of the inferior articular processes, the laminae, the ligamentum flavum, and sometimes the spinous processes. On the contrary, lateral or nerve-root canal stenosis (foraminal stenosis) is caused by pathology of the superior articular processes and involves the emerging nerve roots, either alone or along with the lateral portions of the thecal sac.⁴⁷⁻⁴⁹

Foraminotomy is a form of decompression surgery suitable for compromised nerve roots, first described by Briggs and Krause in 1945.⁵⁰ Two approaches for conventional foraminotomy exist: the midline approach, used for decompression of traversing nerve roots, and the paraspinous approach, used for decompression of exiting nerve roots (Fig. 64.4). If foraminotomy is performed in addition to a laminectomy or laminotomy, a medial part of the pars



Figs. 64.5A and B: (A) Illustration shows that bilaminotomy on right laminae (stippled area, arrow) and reaching to the opposite side under the interspinous ligament and through undercutting the base of spinous process. (B) Axial view shows nerve root and dural protection while contralateral undercutting.

Source: Original drawings of the unilateral laminotomy for bilateral decompression through midline approach by McCulloch JA, Young PH. Musculoskeletal and neuroanatomy of the lumbar spine. Chapter 18. In: *Essentials of Spinal Microsurgery*. Philadelphia: Lippincott-Raven; 1998.

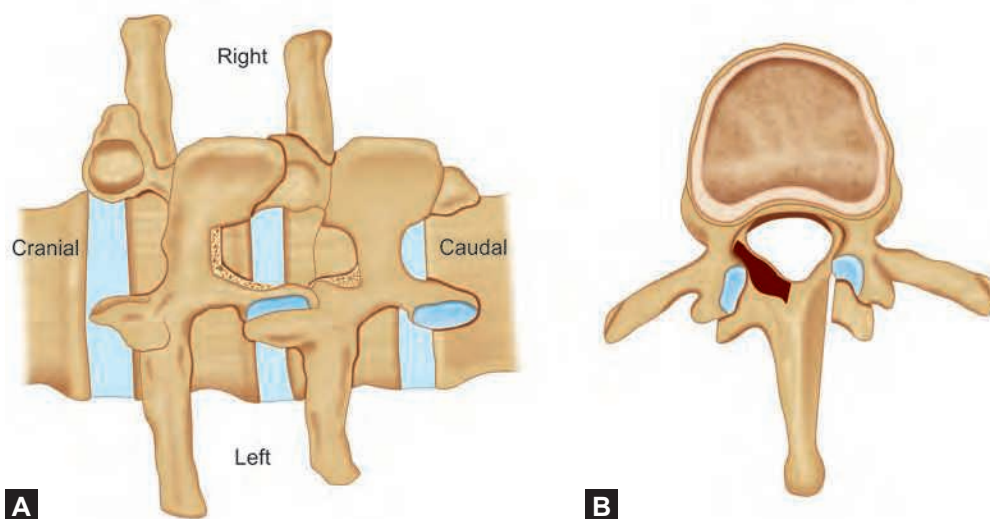
interarticularis along the traversing nerve root and a portion of the superior articular processes, where they come together forming the facet, are removed. Excessive removal of ipsilateral pars or medial facet may cause fracture of the inferior articular processes or spinal instability.^{51,52}

Facet Joint-Sparing Laminotomy and Foraminotomy

In 1980, Ciric et al.⁵³ proposed lateral recess stenosis as a variant of lumbar spinal stenosis. The lateral recess is the region of the lumbar canal that is bordered laterally by the pedicle, posteriorly by the superior articular facet and ligamentum flavum, and anteriorly by the vertebral body, endplate margin, and disc margin (see Fig. 64.3).⁴⁷ This region corresponds to the supra-axillary region as anatomically defined by Wilmink in 1989.⁵⁴ In cases of unilateral spinal lateral recess stenosis or foraminal stenosis, when employing a midline ipsilateral approach, the retained midline posterior structures can obstruct the view and trajectory of instruments introduced for undercutting the lateral zone. To enhance ipsilateral decompression without violation of facet joint stability, Yong-Hing and Kirkaldy-Willis introduced in 1978 a spinous process osteotomy procedure, and modifications thereof, to increase the surgical exposure of the posterior structures. This permitted facile examination of the lateral recess and foramen, but

it unfortunately caused excessive spinous instability.⁵⁵⁻⁵⁷ Facet joint-sparing foraminal undercutting via the contralateral side can be performed through either midline or paraspinal approaches as a method for minimizing the removal of medial articular bones that is normally performed as a part of the ipsilateral approach. In 1988, Aryanpur and Ducker⁴⁵ demonstrated a multilevel midline unilateral approach with bilateral decompression while preserving contralateral zygapophyseal joints, and Young et al.⁵⁸ described the preliminary report of multilevel subarticular fenestration through a midline approach. The anatomical considerations of the unilateral laminotomy for bilateral decompression through midline approach were described by McCulloch and Young⁴⁰ (Figs. 64.5A and B).

In 1953, Watkins⁵⁹ described a lateral approach to the lumbosacral spine that involved separation of the sacrospinalis and quadratus lumborum muscles to expose the transverse processes. Wiltse modified this approach in 1958 opting instead for a longitudinal separation of the sacrospinalis (erector spinae) muscle group between the multifidus and longissimus muscles to expose the facet joints and transverse processes.^{36-38,45} Wiltse and Spencer³⁸ further refined this paraspinal approach and described this procedure in 1988 as what was first called unilateral laminotomy for bilateral decompression of lumbar spinal stenosis by incorporating a sacrospinalis muscle-splitting technique.¹⁸ The anatomical and surgical considerations



Figs. 64.6A and B: (A) The hatched area demonstrates bilaminotomy and undercutting the adjacent base of the spinous process (surgeon's view). (B) Lines drawing demonstrate the angles of the exposure. The medial angulation of the operating microscope allows the contralateral removal of the ligamentum flavum and leads easy access to the contralateral lateral recesses and foramina.

Source: Original drawings of the unilateral laminotomy for bilateral decompression through a paraspinal approach by Spetzger U, Bertalanffy H, Naujokat C, et al. Unilateral laminotomy for bilateral decompression of lumbar spinal stenosis. Part I: anatomical and surgical considerations. *Acta Neurochir.* 1997a;139:392-6; Spetzger U, Bertalanffy H, Reinges MHT, et al. Unilateral laminotomy for bilateral decompression of lumbar spinal stenosis. Part II: clinical experiences. *Acta Neurochir.* 1997b;139:397-403.

of the unilateral laminotomy for bilateral decompression through a paraspinal approach were finally established by Spetzger et al.^{60,61} in 1997, who described the procedure as an ipsilateral laminotomy and foraminotomy with contralateral undercutting of the lamina, with the possibility of removing the medial side of the hypertrophied superior facet (Figs. 64.6A and B). Tubular retractor-guided to the facet joint-sparing unilateral laminotomy for bilateral decompression in the paraspinal approach was introduced and performed clinically by Khoo and Fessler⁶² and Palmer et al.⁶³ in 2002 (Figs. 64.7A to F). Facet joint-sparing tubular retractor-guided contralateral approach is useful to treat degenerative spinal disease and benign mass lesion such as facet joint cyst as well.^{64,65}

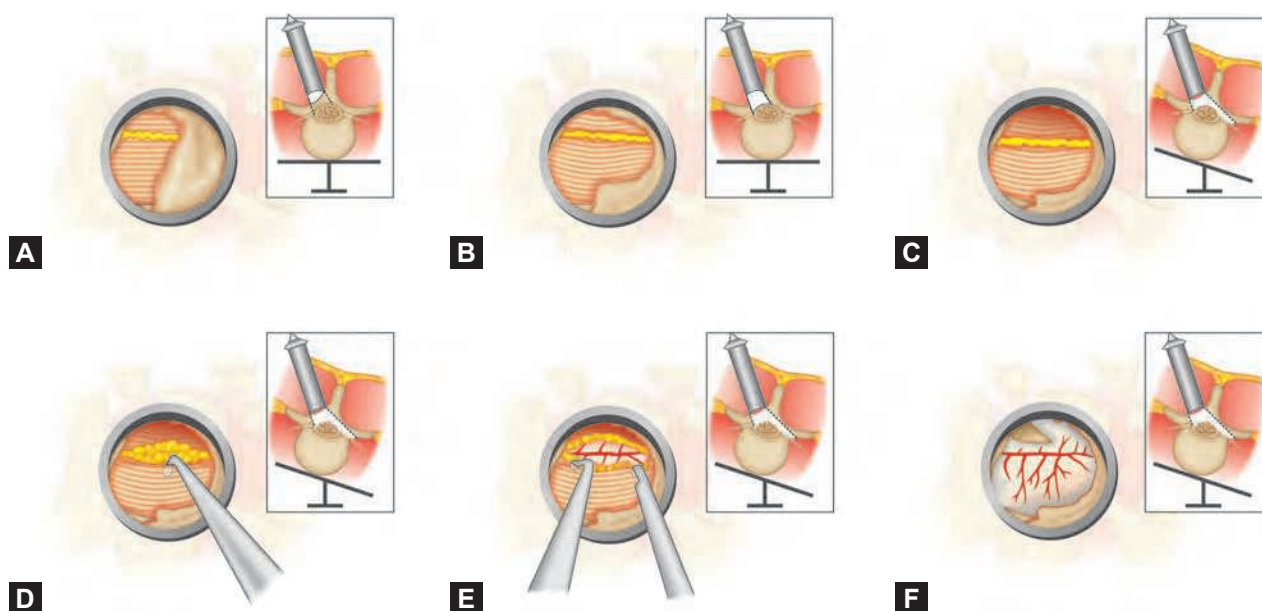
POSTERIOR LUMBAR INSTRUMENTATION PROCEDURES

Since 1911, when Hibbs and Albee first reported the posterior spinal fusion procedure with tibia bone graft for Pott's disease, many modified methods for lumbosacral fusion have been developed.^{59,66,67} The term posterolateral fusion (PLF) was first coined by Campbell⁶⁸ in 1939. Fusion bed preparation was defined by Watkins⁵⁹ as the foremost

important step in PLF, whereby bony decortication is performed in the posterolateral region of the lumbosacral spine, which consists of the articular facets, the pars interarticularis, and the dorsal aspect of the transverse processes.⁵⁹

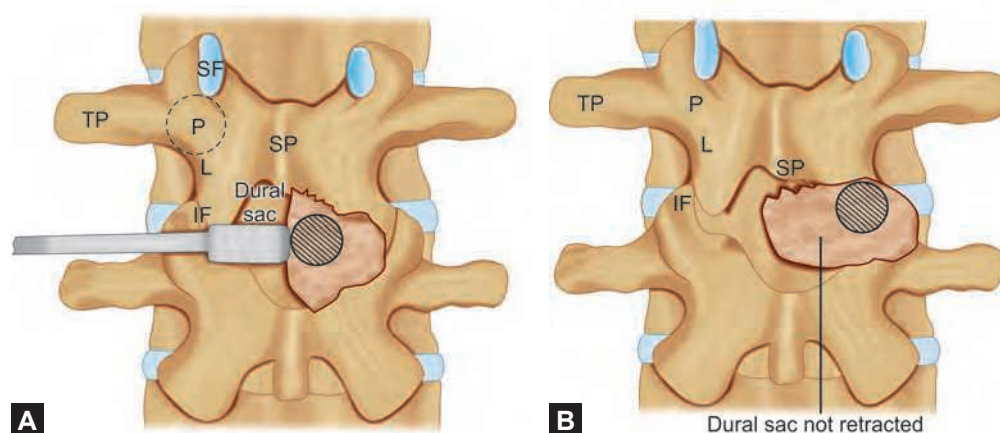
In 1943, Cloward⁶⁹⁻⁷² was the first to perform the posterior lumbar interbody fusion (PLIF) using a full thickness iliac bone graft for the treatment of ruptured lumbar intervertebral disks. Since then, PLIF has become a widely accepted surgical procedure for degenerative spinal diseases such as central canal stenosis, lateral recess or foraminal stenosis, spondylosis, and spondylolisthesis—virtually all procedures of which require wide posterior decompression with facetectomy. But standalone PLIF with inappropriately sized or malpositioned interbody fusion devices cannot produce enough distraction of the annulus fibrosus and therefore limits restoration of lordosis and may ultimately cause biomechanical instability. In these instances, supplemental stabilization techniques may be required.⁷³⁻⁷⁶

The increased risks for instability led to the parallel development of pedicle screw fixation systems. Posterior lumbar interbody fusion performed with pedicle screw fixation has markedly enhanced fusion success rate.⁷⁷⁻⁸⁰ In 1981, Blume and Rojas⁸¹ described a unilateral



Figs. 64.7A to F: Modern unilateral laminotomy for bilateral decompression through tubular retractors in combination with tilting table method. Note preservation of ligamentum flavum until achieving bilaminectomy and contralateral decompression (A) tubular orientation and anatomical view after initial docking (B and C) and initiation of removing the ligamentum flavum from the midline where the two leaves of the ligamentum flavum meet—an area that is typically identified by the presence of epidural fat (D to F). These techniques minimize the risks of injury to the dura.

Courtesy: Roger Härtl is a professor of neurological surgery, the director of spinal surgery and the director of the Weill Cornell Center for Comprehensive Spine Care, New York City, USA.



Figs. 64.8A and B: (A) Illustration shows posterior lumbar interbody fusion (PLIF), which the stippled area represents bilaminotomy with mostly preserving the facet joint. But ipsilateral root and dura retraction is required for introducing the interbody fusion cages (hatched area). (B) Illustration shows transforaminal lumbar interbody fusion (TLIF) without retraction of root and dura. The stippled area represents medial and lateral facetectomy, which lead necessity of supplementary transpedicular stabilizing instrumentations. (SP: Spinous process; P: Pedicle; TP: Transverse process; IF: Inferior facet; SF: Superior facet; L: Lamina).

approach to PLIF that was introduced in response to the neurological complications associated with the original PLIF technique. Regardless of whether the procedure is performed unilaterally or bilaterally, the PLIF approach requires medial retraction of the thecal sac and traversing

nerve roots for insertion of interbody fusion cages (Fig. 64.8A). This process is associated with risks for neurological damage. To minimize posterior musculotendinous and neural retraction injury and to facilitate the placement of interbody fusion cages, transforaminal

lumbar interbody fusion (TLIF) was introduced by Harms (Fig. 64.8B).⁸²⁻⁸⁵

Vertebrectomy with stabilization have been frequently performed using a two-stage operation with an anterior and a posterior stage. Magerl and Coscia⁸⁶ and Shaw et al.⁸⁷ described a single-stage operation, which involves a posteriorly performed transpedicular corpectomy with posterior stabilization. The introduction of expandable cages made this a more affordable reconstructive surgery, all the while correcting sagittal deformities and improving neurological outcome.⁸⁸

Axial Lumbar Interbody Fusion (AxiaLIF) is an alternative fusion method for vertebral levels L4-S1. Although this surgical method is mostly performed blind and involves unique complications such as rectal injury, fistula, and pelvic hematoma, which require additional surgical planning on the part of spinal surgeons, the overall complication rate of AxiaLIF is relatively low relative to PLIF and TLIF, and is similar to those reported for anterior lumbar interbody fusion approaches.⁸⁹⁻⁹³ However, downsides of this approach include the difficulties with restoration of lordosis, foraminal decompression, and potentially low fusion rates.⁹⁴

MINIMALLY INVASIVE LUMBOSACRAL SURGERY

While macrosurgical exposure surgery has historically had successful neurological outcomes, side effects associated with these surgeries, including iatrogenic back pain, are often unavoidable due to mechanical and ischemic injury of the posterior musculotendinous structures by retraction and/or scar tissue formation—this remains a major concern for modern surgeons and patients.^{1,10,25} To leave the smallest possible “surgical footprint” while still achieving a similar level of surgical and clinical success to that of macrosurgical exposure is the rationale behind MISS. The “four pillars of MISS”—four core principles of orthopedic and neurological surgery that are making MISS possible—consist of microsurgical techniques, minimizing soft tissue injury by the use of less invasive retractor and access technology, navigation, and specialized instruments and implants.⁹⁵⁻⁹⁷ The field of MISS is driven by demand from surgeons and patients, and represents a paradigm shift in the way that spinal surgery is being performed.¹

Development of minimally invasive spinal techniques began with the development of specular and tubular retractors, which resolved the issue of excessive paraspinal tissue damage caused by conventional, macrosur-

gical preparation of visual fields. In 1995, Smith et al.³² introduced the use of tubular retractors which enhanced overall visibility of the surgical field and facilitated the use of microscopic visualization. Initially, tubular retractors were used in laminectomy and discectomy.^{32,98} Later improvements in intratubular visibility allowed for the development of tubular retractor-guided TLIF.²⁹ Tubular retractor-guided minimally invasive TLIF combined with unilateral approach for bilateral decompression and 3D neuronavigation-guided screw placement has since become standard protocol for cases of bilateral root compression with instability.^{31,99}

In addition to technique changes, disadvantages and complications of macrosurgical exposure may spawn new instrumentation, like in the advent of the percutaneous external fixation systems and the internal fixation-based pedicle screw-and-rod system. The use of mechanical systems for placement of rods may mark the beginning of minimally invasive spinal instrumentation.^{100,101} Development of image-guided navigation and associated technologies is also essential for MISS procedures for securing accurate localization of pathology and implant placement on the basis of nondirect visual anatomical references.^{1,102} One current trend is the development of MISS in spinal deformity correction and scoliosis surgery, such as in the use of minimally invasive techniques in multilevel percutaneous pedicle screw and connecting rod placement for extreme lateral interbody fusion or direct lateral interbody fusion.¹⁰³⁻¹⁰⁵

Endoscopic Disc and Decompression Surgery

Initially endoscopy was used for percutaneous biopsy or for inspection of the intervertebral space following open surgery. Subsequently, this procedure had been developed with instrumental improvement into the so-called endoscopic transforaminal technique.¹⁰⁶ The endoscopic posterolateral transforaminal approach targets both exiting and traversing spinal nerves and can be used to directly remove intraforaminal and extraforaminal sequestered discs. For pathologies located in the spinal canal, an interlaminar approach is available.¹⁰⁷ Tsou and Yeung¹⁰⁸ and Yeung and Tsou¹⁰⁹ described the “in-out technique,” which involves an intradiscal removal of a prolapsed disc through the annular defect. Although the endoscopic approach is technically most minimally invasive, the limited mobility of instruments, the impossibility to repair any iatrogenic dura injury, and the stiff learning curve are still problems to overcome.¹¹⁰

Choice of Posterior Approaches to the Lumbosacral Spine

In recent years, spinal operative concepts have evolved rapidly, including access trajectories, operative techniques, static versus dynamic instrumentation, and minimal invasive procedures. Surgical failures can be minimized by correctly choosing the appropriate posterior approach to the lumbosacral spinal lesion. Such decisions are multidisciplinary, and many factors can affect operative results.

The choice and method of trajectory is mainly dependent on the location of spinal pathologies and is influenced by experience and preferences of the surgeon. Furthermore, it is important to understand the feasibility of the surgical technique and to weigh the risks-to-reward ratio in determining what approach to use: conventional versus minimally invasive methods. For example, if a patient presents with mild spondylolisthesis with transient radicular pain, either surgical trajectory—anterior or posterior—can be considered, and the ultimate decision depends on preferences of the surgeon and the patient.

Special considerations are necessary as surgical planning for real cases can be more complex than just selecting a surgical approach and technique. For instance, the skin and underlying soft tissues of recently radiated patients are vulnerable to bleeding and infection, and such patients would require special considerations when it comes to surgical planning.¹¹¹ For overweight patients, careful positioning should be considered when placing them on the operating table for a posterior approach in order to prevent excessive intra-abdominal pressure. Details of the preoperative plan may be influenced by the site of operation, surgical revisions, and the nature of the pathological process itself. In addition, the need to remove bone, or the extent to which skin and fascia need to be excised, can also implicate the choice of approach. Another important consideration is cosmetic effects, such as operative scars, which may influence the patients' choice on surgical trajectory and methods. Cost effectiveness is also of concern; for instance, in Artificial Total Disc Replacements, or in surgical placement of motion-sparing devices through anterior or lateral approaches, clinical outcomes have yet to deem them better than conventional posterior fusion despite higher costs.¹¹² Furthermore, the ability of disc replacements to preserve mobility can often be limited. Complications including heterotopic ossification, spontaneous fusion, and device-related failures are still of

concern for motion-sparing devices; moreover the benefit of these devices in preventing adjacent level degeneration still requires further confirmation.¹¹³⁻¹¹⁶ One must consider the maturity of new treatments utilizing the latest technologies in bioengineered artificial disks, biomechanical instrumentation, and bony fusion material in surgical decision-making, since while these new ideas have yet to undergo the test of time in practice; nevertheless, they may transform the way future surgeons perform posterior lumbosacral surgery.

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Surgical Approaches and Reconstruction of the Sacrum

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Snapshot

- » Anatomy
- » Classification of Sacral Resection
- » Surgical Approach
- » When is Reconstruction Necessary?
- » Reconstruction Strategies
- » Outcomes

INTRODUCTION

Pathologies involving the sacrum are diverse and rare. Approach and, when necessary, reconstruction of the sacrum is challenging because of its unique anatomical features, biomechanical role, and close apposition to other important structures outside the usual expertise of the spinal surgeon. The complex anatomy of the pelvic region makes resection of sacral tumors a multidisciplinary undertaking. Proficiency in the different surgical techniques of sacral reconstruction is often hard to acquire because of the rarity of their application.

Tumors of the sacrum account for 1–7% of all spinal tumors.¹ Because of their nonspecific initial symptomatology, they tend to be large and locally advanced at the time of diagnosis. They can also be overlooked radiologically, both because of incomplete sacral imaging techniques and because of the intrinsic sacral anatomical properties, which can make lesions in this area hard to define.² The majority are metastatic lesions originating from either hematogenous or solid primary malignancies. The most common primary malignant tumor of the sacrum is a chordoma, while the most common benign tumor is a giant cell tumor. The optimal management of sacral tumors is determined by numerous factors including anatomical characteristics of the tumor, preoperative functional status of the

patient, and, more importantly, intrinsic biology of the tumor.³ While oncologic cure is seldom a goal in metastatic disease, it often is for primary spinal tumors. In fact, surgery plays a key role in the management of most primary tumors. The Enneking classification, originally described for tumors of the appendicular skeleton, remains the fundamental foundation for approaching primary mesenchymal tumors, including those originating from the spine.⁴ For each Enneking stage, a specific resection margin is recommended.⁵ Because most primary tumors originating in the sacrum are chemo- and radio-resistant, en bloc resection with adequate margins is often the only method of achieving local control. Moreover, adhering to the Enneking principles has been correlated with reduced local recurrence rate, improved tumor-free survival, and improved life expectancy, while maintaining acceptable morbidity and health-related quality of life outcomes.^{6–13} Respecting the Enneking principles for aggressive benign and malignant tumors of the sacral region is technically challenging, both from a resection and reconstruction perspective.

This chapter focuses on surgical decision making for reconstruction of the sacrum. Relevant anatomy, biomechanics, reconstruction indications, and strategies are reviewed. A more detailed discussion on sacral tumors will be provided in other chapter of this book.

ANATOMY

A basic tenet of performing any surgical procedure is a good understanding of the relevant anatomy. The human sacrum consists of five separate sacral vertebrae that fuse to form a large triangular-shaped bone. Fusion of the sacrum begins at puberty and is usually complete by 25–33 years of age.¹⁴ The end result reflects the axial load-bearing function of the human sacrum, incorporating the wide sacral ala on each side. The sacrum is concave anteriorly, both in the rostrocaudal and in the mediolateral planes, and convex posteriorly. The sacrum is separated anteriorly from the upper part of the rectum by the sacral plexus, and, at the lower part of the rectum, only a dense fascia intervenes between the two structures.¹⁵ The sacrum articulates superiorly with the L5 vertebral body through the L5-S1 intervertebral disc and the facet joints; inferiorly with the coccyx through ligamentous attachments or bony union; and on each side with the iliac bone through the sacroiliac joints. The sacroiliac joints are synovial structures and end at the S2 level. The lumbosacral junction is located anterior to the sacroiliac joint complex, creating a rotatory force on the sacrum. The force vector is counterbalanced by strong ligaments: the interosseous and posterior sacroiliac ligaments are the strongest of these, resisting forward tilt of the upper end of the sacrum. Other ligaments include the sacrotuberous and sacrospinous ligaments, which resist posterior tilt of the inferior sacrum and coccyx, and the iliolumbar ligaments, which resist forward migration of the L5 vertebral body.¹⁶ Forces are transmitted from the spine to the sacrum and then to the pelvic girdle via the sacroiliac joints.¹⁷ Consequently, spinopelvic stability is not compromised as long as these structures are preserved (see below).

Although a detailed vascular and neural anatomy of the pelvic region is beyond the scope of this chapter, its knowledge is essential before undertaking sacral resection. In fact, at presentation, sacral tumors are often so large that they may distort normal vascular anatomy. The presacral venous plexus may become congested and dilated and be a cause of significant blood loss if overlooked. Preoperative embolization is very useful to better define the patient's specific vascular anatomy and to limit intraoperative blood loss.

CLASSIFICATION OF SACRAL RESECTION

Fourney et al.¹⁸ reported on the Texas MD Anderson Cancer Center experience with sacral neoplasm.¹⁸ On the

basis of their experience on 29 consecutive patients, who underwent en bloc resection of primary sacral tumors, they proposed a novel classification based on the level of nerve root sacrifice as opposed to the level of osteotomy. They divided the type of sacral resections into two groups: those used for midline lesions and those used for eccentric tumors. The midline sacral resection group was further subdivided based on the level of the nerve root sacrifice (Fig. 65.1). Low sacral amputation was defined as sacrifice of S4 nerve roots and below, midsacral amputation as sacrifice of at least one S3 nerve root, and high sacral amputation as sacrifice of at least one S2 nerve root or when only unilateral S1 root sacrifice was necessary. For more locally advanced tumors, when both S1 nerve roots had to be divided a total sacrectomy was performed. When the tumor extended beyond the sacrum to involve the lumbar spine as well, a translumbar amputation or “hemisacrectomy” was performed. The eccentric group included en bloc resection of one sacroiliac joint and hemisacrectomy. This classification of sacral resection has since been used by other centers with lots of experience in dealing with en bloc sacral resections.¹⁹ Another surgical classification for sacral tumors based on anatomical position in the sagittal and cross-sectional plane, as well as anterior extension into the pelvic cavity, has also been proposed.²⁰

SURGICAL APPROACH

Once local and systemic staging is completed, histopathological diagnosis is confirmed, and en bloc resection deemed necessary based on evidence-based principles, multidisciplinary surgical planning takes place. It cannot be overstated that most of these cases require multidisciplinary expertise. The level of the sacrectomy is decided based on the extent of bony involvement and the most proximal roots involved. The expected neurological deficits should then be discussed with the patient to obtain operative consent. The relationship between the anterior extension of the tumor, rectum, and retroperitoneal vessels will also guide the choice of the approach. If the posterior wall of the rectum is involved, a general surgery colleague should be consulted and a diverting colostomy considered. Vascular structures within the pelvis can also be displaced or involved by the tumor, in which case a vascular surgeon can be of a great aid to facilitate the dissection. Finally, a plastic surgeon is often required because of the extensive cavity created by the resection and to assist with flap closure.

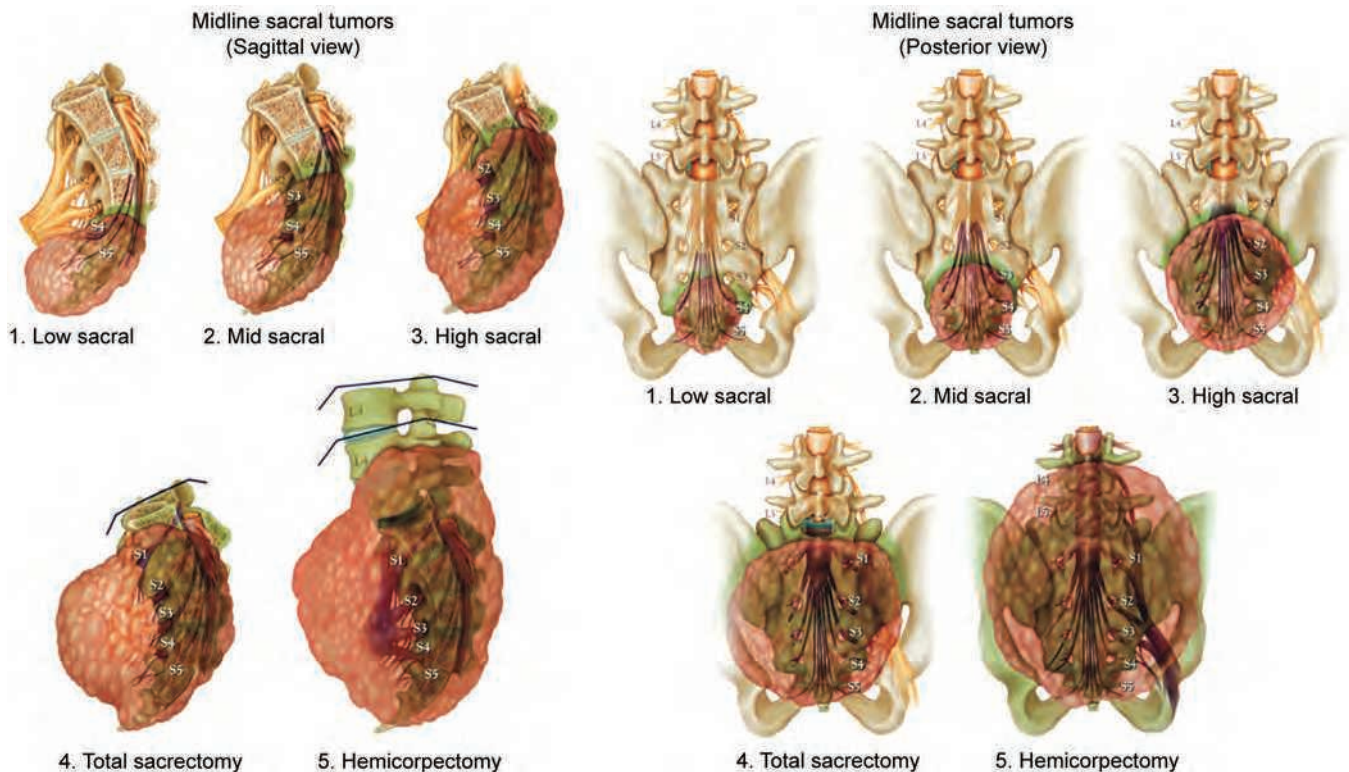


Fig. 65.1: Levels of sacral resection for midline sacral tumors.

Source: With permission from Fourney DR, Rhines LD, Hentschel SJ, et al. En bloc resection of primary sacral tumors: classification of surgical approaches and outcome. *J Neurosurg Spine*. 2005;3(2):111-22.

Anterior, posterior, combined, and simultaneous approaches have been described in the literature. The goals of the anterior approach are to dissect the anterior portion of the tumor and to ligate the main tumoral vessels.²¹ It allows for careful mobilization of the rectum as well. The anterior approach is also used to harvest the rectus myocutaneous flap that can be used to fill the surgical void in high sacrectomies. The posterior approach is then used to deliver the tumor and to proceed with reconstruction. The combined anterior-posterior approach is mainly used for hemisacrectomy, total sacrectomies, and selected high sacrectomies.^{16,19,21,22} A simultaneous anteroposterior approach is also described,²³ but is often not the preferred approach since it is difficult to expose both anteriorly and posteriorly—as well as when they are done separately—and the approach complicates subsequent reconstruction.¹⁶ The posterior approach alone is appropriate for most high, middle, and low sacral resections.^{16,19} Mc Loughlin et al.²⁴ described a total sacrectomy performed in a single-stage posterior approach. There are three factors that preclude the use of a single-stage posterior approach: tumoral involvement of the rectum, tumoral extension

into the lumbar spine requiring a hemisacrectomy, and involvement of the iliac vessels.²⁵

■ WHEN IS RECONSTRUCTION NECESSARY?

Aside from the already challenging primary oncologic goal of the surgery, restoration of spinopelvic stability is also of paramount importance. A landmark biomechanical study by Guntenberg in the 1970s showed that a partial sacrectomy done at the S1-2 level weakens the pelvic ring by about 30%, and a more extensive submaximal sacrectomy done 1 cm below the sacral promontory, preserving 50% of the sacroiliac joints, weakens it by about 50%.²⁶ On the basis of the physiologic loads transmitted from the sacrum to the pelvic girdle, the authors concluded that weight bearing was safe without reconstruction, as long as at least 50% of the sacroiliac joints were preserved on each side, corresponding to at least the upper half of the S1 vertebra. This indication for stabilization is accepted in the literature.^{18,19} Even if the sacrospinous and sacrotuberous

ligaments are transected with these lower sacral resections, the strong sacroiliac joint-posterior sacroiliac ligament complex suffices to assure stability. The potential for fatigue fracture after high sacral amputation seems to be of limited clinical significance. Bergh et al.⁷ reported that six of 18 patients with high sacral resection (at or above the S1-S2 disc space) developed fatigue fracture in the remaining part of the sacrum.⁷ However, only one patient suffered from disabling pain despite surgical intervention. No patient with sacral amputation below the S1-S2 disc space developed insufficiency fractures. Another biomechanical study, however, concluded that reconstruction should be considered when the sacrectomy is done cephalad to the S1 foramina.²⁷ Hugate et al.²⁷ also showed that the pattern of failure was vertical fractures through the sacrum (most often Dennis zone II), while none of their specimens failed at the sacroiliac joint level.²⁷ Another more recent biomechanical analysis showed that partial transverse sacrectomy involving S1 could result in rotational instability, and resection of greater than half of S1 further leads to compressive instability. The authors then concluded that reconstruction should be considered if the resection is at or above the S1-S2 level.²⁸

When a total sacrectomy is performed, the lumbar spine is entirely disconnected from the pelvic ring and hence surgical reconstruction is indicated despite the added complexity and potential morbidity.^{18,19,29} Reconstruction allows for earlier mobilization and return to activities. Some authors advocate that reconstruction should be avoided because of the risk of infection and hardware failure.^{30,31} Stability is then dependent on the formation of a biologic sling composed of muscle and scar tissue between the pelvis and the lumbar spine. Prolonged immobilization is however required if no reconstruction is attempted. For hemisacrectomy and unilateral sacroiliac joint removal, some recommend upfront stabilization¹⁹ (Fig. 65.2), while some do not routinely perform lumbopelvic reconstruction if the contralateral joint is intact and there is no anterior pelvic deficiency.¹⁸

RECONSTRUCTION STRATEGIES

Multiple lumbopelvic reconstruction techniques have been described.^{16,19,21,29,32-38} Most techniques used are a modification of the Galveston method initially described for neuromuscular scoliosis.³⁹ Gokaslan et al.²⁹ described a modified Galveston L-rod technique for sacral reconstruction after total sacrectomy in two patients harboring a sacral giant-cell tumor. The original technique involves the placement of bilateral L3-L5 pedicle screws. A ver-



Fig. 65.2: Example of a complex reconstruction using a vascularized fibula graft, and instrumentation bridging L3 to ischial tuberosity on the right, and L3 to ileum on the left following a hemipelvectomy and complete resection of the right-sided sacroiliac joint.

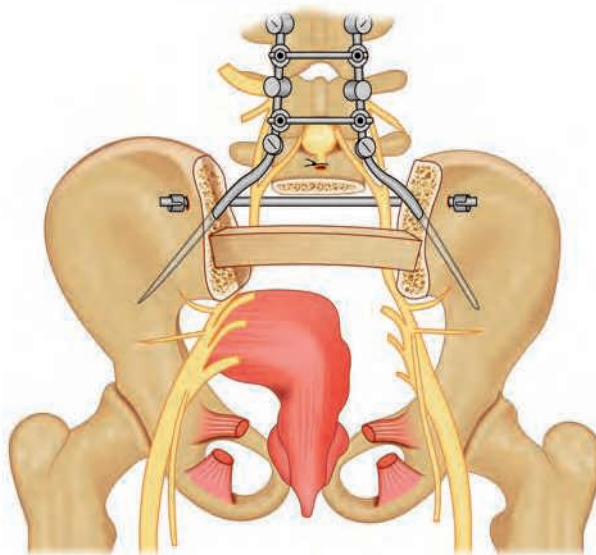


Fig. 65.3: Illustration of the initial modified Galveston L-rod technique.

Source: With permission from Gokaslan ZL, Romsdahl MM, Kroll SS, et al. Total sacrectomy and Galveston L-rod reconstruction for malignant neoplasms. Technical note. *J Neurosurg.* 1997;87(5):781-7.

tical rod is then placed on each side from the pedicle screws proximally and then bent laterally in between the two cortices of the ilium distally. Cross-connectors are used to secure the construct. To prevent axial rotation, a transiliac bar is then placed to fix iliac bones to each other. A tibial allograft is used to close the space between the two ilia. A combination of autologous and allogeneic bone graft is

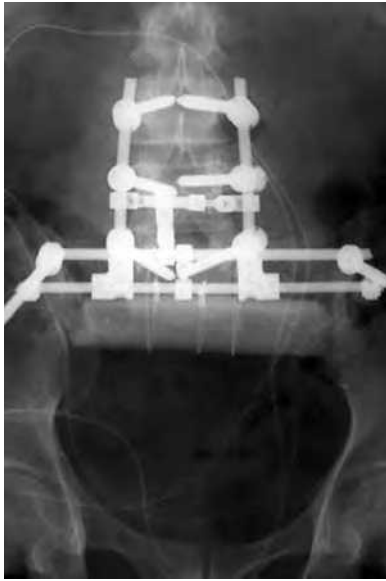


Fig. 65.4: Postoperative X-ray, depicting the updated modified Galveston technique.

Source: With permission from Gallia GL, Haque R, Garonzik I, et al. Spinal pelvic reconstruction after total sacrectomy for en bloc resection of a giant sacral chordoma. Technical note. J Neurosurg Spine. 2005;3(6):501-6.

placed from the transverse processes of L3 to the medio-posterior aspect of the ilium to achieve solid bony union (Fig. 65.3). With follow-up, this construct was found to suffer from some biomechanical limitations. More specifically, this method does not optimally resist axial and rotational forces across the horizontal axis resulting in rod breakage between the L5 pedicle screws and the ilium, and loosening of the iliac portion of the rod, respectively. To overcome these limitations, Gallia et al.³⁶ described an updated version of the modified Galveston technique using poly-axial iliac screws instead of the L-shaped rod. Iliac screws overcome the potential drawback of the difficulty associated with contouring the Galveston rods. A transiliac bar was used and connected to the pedicle screw rods using L-shaped connectors. A rod connecting the iliac screws was then linked to the construct using various cross-connectors (Fig. 65.4).³⁶ Later, a four-rod technique involving bilateral dual iliac screws was described to better address the problem of rod fracture at the lumbo-pelvic junction (Fig. 65.5).³²

Another method of spinopelvic reconstruction, called triangular frame reconstruction, was described by Murakami et al.⁴⁰ After a total sacrectomy has been performed, the spinal column is pulled down (3 cm) and L5

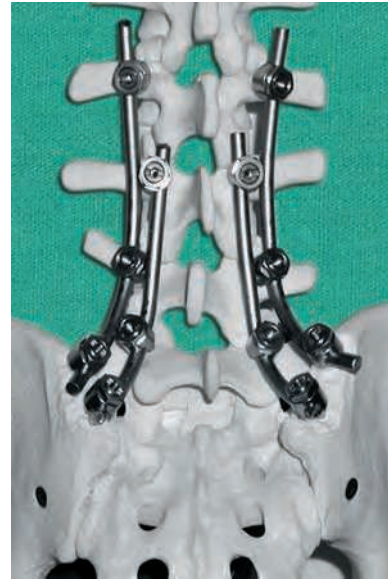


Fig. 65.5: Model showing the four-rod with bilateral dual-iliac screws technique.

Source: Spine by Lippincott Williams & Wilkins. Reproduced with permission of Lippincott Williams & Wilkins in the format reprint in a book/textbook via Copyright Clearance Center.

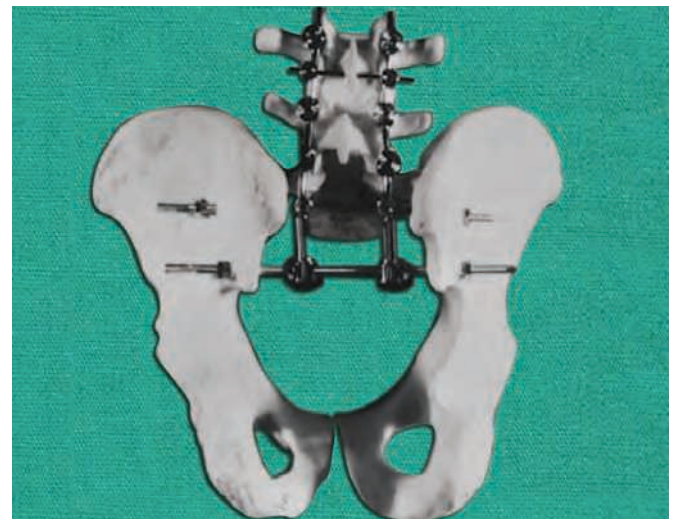


Fig. 65.6: Model depicting the triangular frame reconstruction method.

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is affixed to the ilium bilaterally with a sacral rod. Another sacral rod extending into the pelvis is then connected to the spinal rod, which is affixed to the pedicle screws of L3-L5 (Fig. 65.6).

Kawahara et al.³⁵ conducted a finite-element analysis of reconstruction methods used after a total sacrectomy. In their analysis, they described a novel reconstruction technique consisting of both posterior and anterior instrumentation. The posterior instrumentation consisted of L3-L5 pedicle screws connected to iliac screws via a rod. Anteriorly, they put two pedicle screws in the inferior endplate of L5 which they connected to a sacral rod, itself connecting to both sides of the pelvis. Using this model, Kawahara et al. concluded that there was a low risk of instrument failure and loosening after total sacrectomy. They compared this technique with the modified Galveston and triangular frame reconstruction techniques, and found that the former was associated with excessive stress at the spinal rod level while the latter led to excessive stress at the iliac bone level.

Another technique using two to three pairs of bicortical iliac screws connected to L3–L5 pedicle screws via a single U-shaped rod has been described.^{19,41} This closed-loop technique is believed to provide improved stability of the lumbopelvic junction in flexion–extension and rotation (Fig. 65.7).

To relieve the stress on the posterior instrumentation and the iliac bone, Dickey et al.⁴² described a new form of anterior reconstruction using structural fibular grafts combined with a pedicle screw-rod instrumentation to create a triangular construct along the anatomic force transmission vectors from the femoral heads to the lumbar spine.



Fig. 65.7: Postoperative X-ray showing the closed-loop U-rod reconstruction technique.

In a case of hemicorporectomy, Gallia et al.³³ described a novel technique of lumbopelvic reconstruction using a distractible cage to reconstruct the anterior column.

A custom-made prosthesis has also successfully been tried to restore spinopelvic stability. On the basis of pre-operative imaging and necessary extent of resection, Wuisman et al.³⁴ reported on the usage of a custom-made sacral prosthesis on one patient suffering from a primary osteosarcoma of the sacrum. One disadvantage of this technique is the inability to make any intraoperative adjustments.

The appropriate method of reconstruction largely depends on the experience of the surgeon and on specific tumor/patient characteristics. Multiple biomechanical studies have, however, been conducted to compare some of these sacral reconstruction strategies.^{35,40,43–47} Kelly et al.⁴⁵ compared the four-rod and the two-rod techniques both with and without cross-links. They found that the four-rod lumbopelvic reconstruction technique provided significantly greater stability in flexion and extension as compared to a conventional cross-linked two-rod technique in a human cadaveric sacrectomy model. The four-rod technique also significantly reduced the motion at the L5-pelvic junction, which may be clinically relevant in achieving solid bony union. The addition of cross-links further improved stability in axial rotation. Yu et al.⁴⁴ reported on biomechanical superiority of dual-iliac screw over the single iliac screw method for cases involving high sacrectomies with unilateral sacroiliac joint resection and for total sacrectomies. The dual-rod dual-iliac screw technique provided the most rigid fixation among the four techniques using posterior fixation only.⁴³ The biomechanical advantage of adding anterior support (either L5 inferior end plate screws/sacral rod, triangular fibular flaps, or a compound method) to the four-rod technique has also been demonstrated,^{35,46,47} at the cost of significant technical difficulties and potential disturbance to the pelvic viscera.

Pelvic incidence is a key determinant of sagittal balance. Pelvic incidence does not change in adulthood, despite traditional lumbosacral surgeries. However, with total sacrectomies and total disarticulation of the sacroiliac joints, pelvic incidence is altered.⁴⁸ Although long-term studies are lacking, change in pelvic incidence may be relevant clinically, and thus should be taken into consideration during lumbopelvic reconstruction.

Another important consideration in total and high partial sacrectomies is the significant surgical cavity created by

the resection. Despite advances in reconstructive microsurgical techniques, the repair of the large void created by tumoral resection remains a challenging undertaking.⁴⁹ This task is further complicated by preoperative radiation therapy and difficult access to adequate recipient vessels in the sacral area. The main techniques used are the vertical rectus abdominis myocutaneous (VRAM) flap, bilateral gluteal advancement flap, gluteal rotation flap, gluteal thigh flap, and free flap reconstruction. The VRAM flap is harvested during the anterior approach and, consequently, cannot be used in posterior approach only. The VRAM flap is thus not the preferred reconstructive method for middle and low partial sacrectomies, typically done with a posterior approach alone. Miles et al.⁵⁰ published their experience of 27 flaps in 25 patients and concluded that in patients with no preoperative radiation therapy and intact gluteal vessels, the use of bilateral gluteal advancement flaps should be an option to consider. When there is a history of radiation to the area or if the gluteal vessels are damaged by the surgical resection, the use of a VRAM flap should be considered. When a previous laparotomy precludes the use of the VRAM flap, then a free flap should be contemplated as a final option. Others have, however, reported that a prior laparotomy has no detrimental effect on the effective or safe use of a transabdominal pedicled VRAM flap.⁵¹ The MD Anderson group reported on their 15-year experience on 50 patients.⁵² In their experience, the resection volume was the main factor determining flap choices: gluteus-based flap being most commonly used for small and medium cavities and VRAM flap as the preferred option for large defects. The overall complication rate was 44%, but the flap choice was not an independent predictor of complications.

Another goal of the soft tissue reconstruction is to avoid parasacral herniation of the abdominal content. This can be accomplished by using a mesh⁵³ or the myocutaneous flap itself.⁵¹

In the case of extensive defects created with posterior approach only, Dasenbrock et al.⁵⁴ published their data on 34 patients with sacral tumors in whom reconstruction was achieved using a human acellular dermal matrix along with gluteus maximus myocutaneous flaps. Of note, gluteal arteries are preserved in a posterior-only approach, assuring a robust blood supply to the gluteus flap. They showed this technique to be a valid option with comparable rate of wound complications to other techniques and low rate of parasacral herniation.⁵⁴

OUTCOMES

Neurological Function

From a neurological perspective, sacral roots often need to be sacrificed to achieve an evidence-based en bloc oncological resection, putting bowel, bladder, and sexual function at risk. Cases of low sacrectomies (distal to S3) usually lead to perineal hypoesthesia and may result in sexual dysfunction.³ Sphincter and motor function are usually preserved, however. Todd et al.⁵⁵ showed that preservation of bowel and bladder continence after major sacral resection is possible in the majority of patients following unilateral sacral root resection or if at least one S3 root is preserved in the case of bilateral sacral resection. A strong association between the number of S3 roots preserved and continence was also reported in another study.⁵⁶ Aside from the expected unilateral sensory-motor loss, most patients with unilateral sacral root resection (S1-S5) will have preserved or partially impaired bowel and bladder functions.^{18,55,57} In cases of total sacrectomies with bilateral S1 root sacrifice, clinically relevant motor deficits may interfere with independent mobility. With intact L5 root function, a significant proportion will, however, be able to ambulate independently after rehabilitation.^{18,19,58}

Postoperative Care and Complications

If successful bony and soft tissue reconstruction has been achieved, patients are mobilized as soon as tolerated postoperatively. They are nursed in specialized airbeds to reduce the risk of pressure sore and wound breakdown. The expected deficits are confirmed postoperatively and rehabilitation initiated as soon as possible. Psychological support should also be offered if needed.

Sacral tumor resections are significant surgeries associated with significant complications. They are also demanding for the surgical team: total sacral resection often lasting >10 hours,⁴¹ and even >30 hours for two-stage procedures.²⁹ Significant blood loss is also to be expected with reported values ranging from 6.5 L to 40 L for single-stage operations and 10.1–80 L for two-stage operations.²⁹ Early postoperative deaths have also been published secondary to cerebral infarction and sepsis.⁵⁹ Other major complications include rectal and other visceral injury, vascular injury, hardware failure, unexpected neurological deficit (which can be secondary to traction injury to the lumbar plexus), dural tear, and wound problems.^{37,59} The proximity of the anus, the risk of incontinence, the possibility of unrecognized rectal injury as well as the

large surgical dead space created, all contribute to significantly high wound complication rates of 25 to 46%.^{25,52,56} In a study of 50 patients who underwent a sacrectomy, Guo et al.⁵⁶ showed that bowel incontinence is associated with delayed wound healing. They concluded that bowel diversion procedures should be considered in select cases when bowel incontinence is expected based on the level of resection. Median length of hospital stay between 6.5 and 91 days is reported. These are significantly influenced by the extent of sacral resection,¹⁸ the use of a flap closure, occurrence of adverse events, and bowel incontinence.⁵⁶

CONCLUSION

Low-grade malignant and aggressive benign sacral tumors are best treated with an en bloc resection with appropriate surgical margins. In the sacral region, it involves performing varying extents of sacral resection. These surgical interventions can be very challenging and should be assessed by a multidisciplinary team in a center with such expertise. Depending on the level of the sacrectomy, spinopelvic instability may occur and reconstruction may become necessary. There is currently no consensus about the best reconstruction technique. Decisions should then be made according to surgeon experience, as well as specific patient preferences and tumor characteristics. Because of the inherent surrounding anatomy of the sacrum and also because the often large size of these tumors at the time of diagnosis, there is a significant risk for potentially serious complications. Expected neurological deficits from such interventions should be discussed at length with patients preoperatively. With careful patient selection and meticulous surgical planning, successful clinical outcomes can be anticipated, although further quality of life studies would certainly add to the current literature.

- En bloc resection with appropriate margins is the treatment of choice for low-grade malignant and aggressive benign sacral tumors.
- Sacral resections are technically challenging procedures and are better dealt with in an experienced center with a multidisciplinary team.
- Meticulous surgical planning and patient selection are key in the successful completion of these resections.
- Lumbopelvic reconstruction is necessary when >50% of the sacroiliac joints are resected and allows for earlier mobilization.
- Multiple spinopelvic reconstruction techniques have been described, the best one being determined by surgeon experience and specific patient-tumor characteristics.

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Spinal Pelvic Fixation Techniques

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Snapshot

- » Pelvic Anatomy
- » Biomechanics
- » Types of Lumbosacral Fixation
- » Iliac Screw Technique and Placement
- » Extension of Prior Fusion
- » Complications

INTRODUCTION

Posterior fixation of the spine to the pelvis is helpful in achieving arthrodesis at the lumbosacral junction, a region with several unique features that pose considerable challenges to fusion. The inclusion of the pelvis in spinal instrumentation constructs significantly reduces deleterious forces on sacral fixation, thus decreasing instrumentation failure, and pseudarthrosis. The techniques discussed in this chapter are particularly useful for long segment constructs ending at the sacrum such as used for pediatric and adult spinal deformity. In spinal deformity surgery, the incorporation of pelvic fixation is often crucial for success.¹ Pelvic fixation is also an integral part of spinal oncologic procedures where the sacrum is involved such as in sacral chordoma, and also is extremely useful in cases where the sacrum is lacking quality bone for screw purchase such as in osteoporosis, infection, trauma, or pseudarthrosis.^{1,2} Although technically demanding, a mastery of these techniques is a powerful addition to a spine surgeon's armamentarium.

The concept of fixation of the spine to the pelvis is not new. Harrington instrumentation is credited as the first spinal instrumentation that could be applied across the lumbosacral junction. The technique employs the use of hooks and rods for fixation, which can place distractive or compressive forces depending on direction of the hooks.³ The major drawback of spanning the lumbosacral junction

with a hook and rod construct is the inherent instability of hooks at the sacrum that carries a risk of dislodgement of 26% and a dismal pseudarthrosis rate that approaches 40%.^{4,5}

Luque improved spinal fixation with the addition of sublaminar wires affixed to the rod construct. An L-shaped bend located at either end of the construct served to limit cranial or caudal migration of the rods that might occur with loosening of the wires. The lumbosacral junction still posed a significant challenge to fusion with this system, and pseudarthrosis rates are reported up to 41%.⁶⁻⁸

The introduction of Cotrell-Dubousset (CD) instrumentation offered more points of fixation including, for the first time, the use of pedicle screws. The original technique consisted of long thoracolumbar rods with multiple interlocking hooks and wires.⁹ With multiple crosslinks, this system had a higher rate of complications due to instrumentation.^{9,10} The CD technique was the first to introduce intermittent monoaxial pedicle screws for further fixation.³ Historically, when pedicle instrumentation is applied at the sacrum alone, high pseudarthrosis rates of up to 33% are reported primarily because of poor flexion control, leading to a pull-out rate as high as 70% in older constructs.^{9,11}

The Galveston technique for fixing the spine to the pelvis was introduced by Allen and Ferguson in the 1980s for the treatment of children with neuromuscular scoliosis

and pelvic obliquity.^{6,7,12,13} The technique involves the contouring of rods that are then inserted into the ilium at the level of the posterior superior iliac spine (PSIS).¹⁴ Rods are impacted between the inner and outer tables of the ilium in the narrow portion of bone above the sciatic notch. Rods are secured to the spine with sublaminar wires as popularized by the Luque technique¹⁵ for adolescent idiopathic scoliosis. It was the fixation to the ilium that was believed to offer the greatest improvement over prior constructs.

With the advent of modern pedicle screw and rod systems for posterior spinal instrumentation, the use of iliac bolts has largely replaced the Galveston technique. Current systems are modular, allowing for easier integration to multisegment fusion constructs that limit morbidity to the patient. Iliac screws can easily be incorporated into a construct with or without the use of an offset connector (depending upon cannulation technique used). This ease of incorporation has translated to greater pull-out strength of up to 300% when compared to Galveston iliac rods.^{3,16} Compared to the poor fusion rates with earlier constructs, lumbosacral fusion rates with iliac bolts have been reported to be as high as 92.5% in recent studies.^{17,18} A recent study of patients with long constructs and iliac fixation for high-grade spondylolisthesis shows a fusion rate of 95% in a series of 81 patients.¹⁹ In this chapter, we will discuss pelvic anatomy, biomechanics, and screw insertion techniques.

■ PELVIC ANATOMY

The sacrum consists of five fused vertebrae and serves as the interconnecting bony bridge for each half of the pelvis via the sacroiliac joint. Typically the male pelvis is larger than the female pelvis and can accommodate instrumentation with increased diameter and length. When planning sacral pedicle screws, it is important to understand that generally, the ventral surface is concave and the dorsal surface is convex.²⁰ The sacral promontory refers to the angulation formed by the ventral surfaces of the adjacent lumbar and sacral vertebral bodies. Due to the interdigitating nature of this joint, there is minimal motion at this junction. Multiple ligaments further restrict motion here, including the dorsal, accessory, ventral, and interosseous ligaments.²¹

Preoperative anteroposterior radiographic imaging should be performed so that adequate and consistent nomenclature and counting be performed. Sacralization of lumbar vertebrae refers to the L5 vertebrae congenitally

fusing to the sacrum, creating a six-bone sacrum. Conversely, lack of fusion of the first sacral vertebrae can lead the patient to have six lumbar vertebrae and said to have a “lumbarized” S1.

When considering proper iliac screw trajectories, knowledge of the anatomy of the pelvis is key. Radiographic measurement studies of the ilium show the maximum canal diameter to be found between the PSIS and the anterior inferior iliac spine (AIIS).²² The maximum mean screw lengths that could be accommodated between these structures are as high as 141 mm and 129 mm in males and females, respectively. Computed tomography imaging studies also illustrate two consistently narrow portions of the ilium: near the anterior surface of the sacroiliac joint, and superior to the greater sciatic notch. This is clinically relevant for screw purchase and when encountering resistance with iliac screw instrumentation.

When including the pelvis in posterior spinal constructs, there are several pelvic anatomic considerations that must be understood. Aside from the more dense sacral alae and bony promontory, the majority of the sacrum is cancellous.³ The most critical structures to consider when instrumenting the sacrum are the vasculature, namely, the internal iliac artery and vein bilaterally, as well as the middle sacral artery and vein. Additionally, a clear understanding of the locations of the key neural structures such as the sacral sympathetic trunk and lumbosacral trunk is paramount. Lastly, the colon should always be thought adjacent to the cortex when considering anterior cortical breaches from posterior sacral fixation or iliac fixation.

■ BIOMECHANICS

McCord et al.²³ offer some insight to the success of iliac fixation in cadaveric biomechanical studies. They define the middle of the osteoligamentous column at the junction of the last lumbar vertebrae and the sacrum as the lumbosacral pivot point, a point of great stress. They show that the further anterior the iliac screws extend past the lumbosacral pivot point, the more stable the construct. Therefore, when crossing the sacroiliac joint, the goal should be to place a screw as anterior as possible.

Iliac fixation has also been shown in biomechanical studies to decrease strain on S1 screws, providing superior biomechanical support when compared to L5-S1 interbody support.^{24,25}

Work by O'Brien^{3,26} has defined three zones of the spine for instrumentation purposes, whereby in the

progression of the zones increased stability of the lumbosacral construct is obtained. Zone one is defined as the S1 vertebral body and the cephalad alae. Zone two is the caudal alae and the coccyx; and zone three includes both ilia.

TYPES OF LUMBOSACRAL FIXATION

The most prevalent construct today at the lumbosacral junction are S1 pedicle screws connected to iliac screws. In a calf model, under axial compression, only the addition of iliac screws to an S1 screw reduced the strain on S1. This was compared to a variety of constructs: S1 and S2 screws (cranial or caudal pointing), or intrasacral rods, as in the Galveston technique.²⁵ The major disadvantage of using iliac fixation is that it has the greatest effect on lowering the range of motion.²⁵

S1 screws, when offered alone as the caudal end of a long segment fusion, have a high rate of nonunion, as high as 44%.^{9,11} This is in part due to the cancellous quality of the bone of S1. The goal of S1 fixation is to increase the fixation strength by achieving bicortical purchase, or even tricortical purchase by targeting the sacral promontory. Recent work has shown that technique plays a chief role in the fusion rate and pull-out strength of S1 fixation.²⁷ The most notable of which is a cadaver study showing that tricortical purchase involving the sacral promontory has a mean pull-out strength twice that of bicortical purchase.²⁷

S2 screws have seen decreased use given studies demonstrating poor pull-out strength, and little increase in overall stability of the construct.²⁸ Alar screws have increased pull-out strength compared to S2 screws as they are more medially directed. Unfortunately, the strength of alar screws is also greatly augmented by being bicortical and medial, which is a risk to critical neurovascular structures, namely, the lumbosacral vein and internal iliac vessels. The safest trajectory is approximately 45° lateral, keeping in mind the risk for unintentional sacroiliac joint penetration.³

ILIAC SCREW TECHNIQUE AND PLACEMENT

Moshirfar et al propose two paths for iliac screws: from the PSIS to the superior acetabulum, or, the more preferred trajectory, from the PSIS to the AIIS. The AIIS is a preferred target because it allows for longer fixation and is further from the sciatic notch. With monopolar cautery, the PSIS

of the ilium is exposed. A Taylor or similar retractor can be quite helpful in achieving adequate retraction of soft tissue. An osteotome can then be used to harvest a small wedge of bone. This allows the bolts to be well recessed into the PSIS so that the patient does not feel them when seated. Fluoroscopy is routinely used to find an ideal and safe trajectory to the ASIS. Cadaver radiographic studies by Schildhauer et al.²² have developed working fluoroscopic trajectories that can assist with ensuring the absence of a cortical breach. A combined obturator oblique-outlet view of 45° cephalad and 45° anterior demonstrates a supra-acetabular view known as the “teardrop sign” that represents a superimposition of the PSIS, AIIS, and iliac cortical rim above the sciatic notch. This is an *en face* view of the screw trajectory that defines the cancellous bone that will be cannulated. Next, a Steffee probe (Medtronic Sofamor Danek, Memphis, TN) is used to cannulate the starting point. This probe is preferred because of the broad, flat tip, which requires much more force than a pointed probe to cause a cortical breach into the pelvic cavity. The ilium is then tapped and a large diameter (8–10 mm) screw is inserted.

Prior work has demonstrated the safe placement of iliac screws using image guidance, limiting the patient and surgeon's exposure to radiation.²⁹ Using a freehand technique, a typical angle is 30° lateral from midline and 25° caudal from the vertical plane.³⁰ The greater trochanter can also be palpated and the trajectory is approximately towards this structure. When using a freehand technique, the surgeon must be aware that the less lateral the angle, the greater the chance that the screw will breach into the pelvic cavity. Ideally the longest screw possible should be placed because, as previously mentioned, as the distance from the lumbosacral pivot point increases, so does the resistance to flexion forces, thereby increasing the effectiveness of this screw as a load-bearing anchor.

Recently, an alternative technique known as the S2 Alar Iliac Screw (S2AI) has been championed by Kebaish and others. In this technique, a starting position approximately 2–4 mm lateral and 4–8 mm caudal to the S1 foramen is created. A pedicle probe is then advanced in a lateral trajectory (approximately 40° to the horizontal plane and 40° caudally) towards the AIIS.¹ The ala of the sacrum and SI joint are crossed prior to entering the ilium. Pelvic fluoroscopic views or image guidance may be necessary to determine the ideal trajectory. A 70–90 mm long screw may be used within this path. The benefits of this technique are less soft tissue dissection, and the pelvic bolt head is

in line with the S1 pedicle screw, obviating the need for offset connectors. Furthermore, a screw placed utilizing the S2AI trajectory has a lower profile than a screw placed through the PSIS. The S2AI entry site was found to be, on average, 15 mm deeper than the PSIS entry site with respect to the skin surface.³¹ This helps reduce the chance of wound breakdown in a most vulnerable location.

EXTENSION OF PRIOR FUSION

There is some debate in the literature as to the proper role of sacropelvic fixation.^{19,32-40} Some argue that constructs spanning L1 to the sacrum require pelvic fixation^{30,32} whereas others argue that the patient will likely fuse without accelerated breakdown of the lumbosacral junction until the fusion cross the thoracolumbar junction.⁴¹ Islam et al.⁴² studied extensions of prior fusions to the pelvis in 41 individuals. Pseudarthrosis was significantly more prevalent in patients weighing over 60 kg ($P = 0.017$). Those admitting to smoking preoperatively had a high rate of nonunion (4 out of 6, 67%).⁴³ The decision to use pelvic fixation is clearly based upon multiple factors including a patient's overall health, bone quality, and the proposed length of a construct. All of these contribute to the success or failure of achieving lumbosacral fusion.

COMPLICATIONS

Iliac bolt placement has demonstrated a benefit of increased fusion rates across the lumbosacral junction. In an uncommon patient population, there are some less common complications that are encountered with the use of iliac bolts. When a solid fusion has been achieved at the lumbosacral junction, the minimal motion that will persist across the sacroiliac junction will place stress and strain on the screw. Some screws will fracture and a halo can be seen on imaging. Patients complaining of persistent pain may prompt removal of the screw. In a series of 395 patients, the incidence of iliac screw removal was 6% ($n = 24$), with the chief complain being postoperative pain.⁴³

Screw prominence, especially in thin patients, is a relatively more common reason for iliac bolt removal. As mentioned above, an osteotomy in the medial wall of the PSIS provides a recess that lessens this prominence, but does not necessarily prevent a complication. Alternatively, an S2AI screw may be placed to further decrease the potential for implant prominence.

CONCLUSION

Posterior fixation of the spine to the pelvis can be helpful in achieving a successful fusion at the lumbosacral junction, a region subject to substantial biomechanical forces. An understanding of the anatomy is the key in the safe insertion of instrumentation.

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Lumbar Pedicle Screw Fixation

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Snapshot

- » Anatomy
- » Pedicle Screw Design and Biomechanics
- » Surgical Technique
- » Complications
- » Minimally Invasive Techniques of Lumbar Pedicle Screw Insertion

INTRODUCTION

Although not popularly utilized until the 1990s, pedicle screw fixation in the lumbar spine was first described over 60 years ago. In 1959, Boucher described a technique of augmenting a posterior lumbar fusion with screws directed through the pedicle, creating an “internal splint.” With the addition of careful preparation of the fusion area and well packed bone graft, this strategy allowed for early activity and a reduced incidence of nonunion.¹ Harrington later described a technique using L5 pedicle screws for the reduction and stabilization of L5-S1 spondylolisthesis.² In 1986, Steffee published a method using a segmental plate fixation system that utilized pedicle screws, taking advantage of what he called the “force nucleus”—the point on the vertebral body where the forces from the posterior and anterior elements converge.³

When used as an adjunct to fusion, pedicle screw instrumentation provides several advantages including immediate stabilization and lower pseudarthrosis rates. Some advantages of pedicle screw fixation include fixation across all three columns, a means for deformity correction, early mobilization with potentially decreased rehabilitation time, and minimization of the need for postoperative bracing.⁴ When compared to hook and rod systems, pedicle screws may also allow for a decrease in the number of segments needed for a fusion construct.⁵ In a retrospective review of 39 consecutive patients with adolescent

idiopathic scoliosis undergoing curve correction with lumbar pedicle screws and laminar hooks versus laminar hooks alone, the group receiving pedicle screws exhibited significantly better curve correction.⁶

Pedicle screw instrumentation has been associated with a number of disadvantages as well. Increased infection rate, a steep learning curve, neurologic injury, increased operative time and blood loss, loss of fixation, screw breakage, greater cost, and higher reoperation rates have all been cited as potential disadvantages.⁴ The results of instrumented (using pedicle screws) and non-instrumented fusions have been compared as well, with the consensus being that pedicle screws can decrease the rate of pseudarthrosis but do not necessarily improve overall patient outcomes.⁷⁻¹¹ Given these findings, the use of pedicle screw instrumentation should be considered carefully and employed only if the benefits outweigh the risks.

ANATOMY

The anatomy of the lumbar pedicle, as alluded to by Steffee, makes it particularly useful for obtaining the purchase necessary to provide adequate internal fixation. The pedicle is the strongest portion of the vertebra so it is ideal for the application of forces with segmental fixation.¹² Although the lumbar pedicle is well suited for this purpose, it is also in close proximity to the dural sac and nerve roots. Ebraheim et al. defined the anatomy of the lumbar pedicle

with regard to the thecal sac medially and nerve roots both superiorly and inferiorly. They found the average distance between these structures to be 1.5 mm, 5.3 mm, and 1.5 mm respectively.¹³ In a similar study by Soyuncu et al., the authors calculated the interpedicular distance (i.e. distance from the pedicle to the superior nerve root) and distance from the pedicle to the dural sac to be significantly greater at the L5 level.¹⁴

Regarding the average diameter and direction of the lumbar pedicle, it has been shown that there may be significant variation among individuals, without any clear patterns between races and gender.¹⁵ The lumbar pedicle runs ventrally starting at a point at the midline of the transverse process and the lateral boarder of the pars interarticularis. Going from cephalad to caudad, the lumbar pedicle demonstrates increasing medial angulation with an average angle of 12° at L1, 30° at L5, and up to 39° at S1. The sagittal angle extends in a slightly cephalad direction at L1 and is more caudal at L5. Pedicle diameter varies throughout the lumbar spine with L5 typically being the largest with an average diameter of 18 mm and L1 the smallest at 9 mm.^{16,17}

It is important to recognize morphologic variations in the lumbar spine as well, specifically of the L5 and S1 segments. Transitional anomalies at this level include sacralization of the L5 vertebra or lumbarization of the S1 vertebra. When these variations exist, the anatomy and trajectory of the pedicles can change as well; specifically, sacralization results in reduced dimensions for pedicle height, and sagittal and transverse angles, while lumbarization is associated with a reduced length between the facet joint and the sacral promontory. Careful preoperative planning is therefore necessary to address these changes when they are present.¹⁸

PEDICLE SCREW DESIGN AND BIOMECHANICS

A pedicle screw consists of a head, neck, and body. It has inner and outer diameters with the difference between the two measurements representing the thread depth. The pitch of the screw is the distance between the crests of two adjacent threads (Fig. 67.1). The pullout strength of a pedicle screw is related to these physical dimensions. When a pedicle screw pulls out, the bone between the threads becomes fractured. Thus, the pullout strength of a pedicle screw is related to the outer diameter, distance between the threads, and the quality of bone between the threads with the outer diameter of the screw being the most

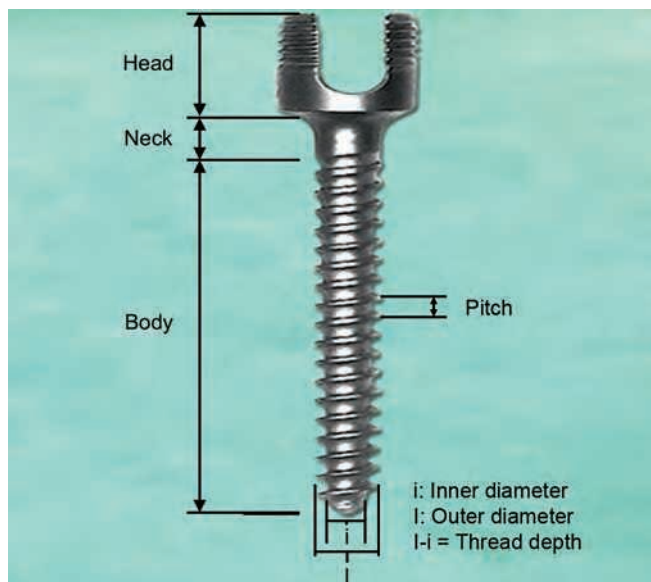


Fig. 67.1: Diagram of a typical pedicle screw.

important characteristic. Pullout strength is also affected by the trajectory of the pedicle screws in that 30° of convergence in the coronal plane is associated with a 28.6% increase in the forces required to bring about failure.¹⁹

The lumbar pedicle itself approximates a cone from dorsal to ventral so screws designed to mimic this shape have been shown to have higher pullout strength. A conical screw has major and minor diameters that refer to the diameter of the screw at the hub and at the screw tip, respectively. In a biomechanical analysis of different types of pedicle screws in calf lumbar vertebra, Inceoglu et al. found that conical screws showed greater stiffness, insertional torque, and pullout strength when compared to traditional cylindrical screws.²⁰

Insertional torque is another property of the pedicle screw and bony interface that is thought to influence pull-out strength although its role is somewhat controversial. In a study by Zdeblick et al. employing 30 human cadaver lumbar vertebra, insertional torque was determined to be directly related to pullout strength with no correlation between pullout strength and bone mineral density.²¹ Okuyama et al. measured the insertional torque of screws that were placed in 62 consecutive patients undergoing posterior lumbar interbody fusion and there was a direct correlation with bone mineral density, but not with screw pullout and failure.²² In the biomechanical analysis cited previously, Inceoglu et al. also reported that changes in screw design affected insertional torque but not pullout

strength.²⁰ Overall, many surgeons prefer a pedicle screw design with high insertional torque due to their superior tactile feedback.¹⁹ However, whether or not this translates into increased pullout strength has yet to be fully determined.

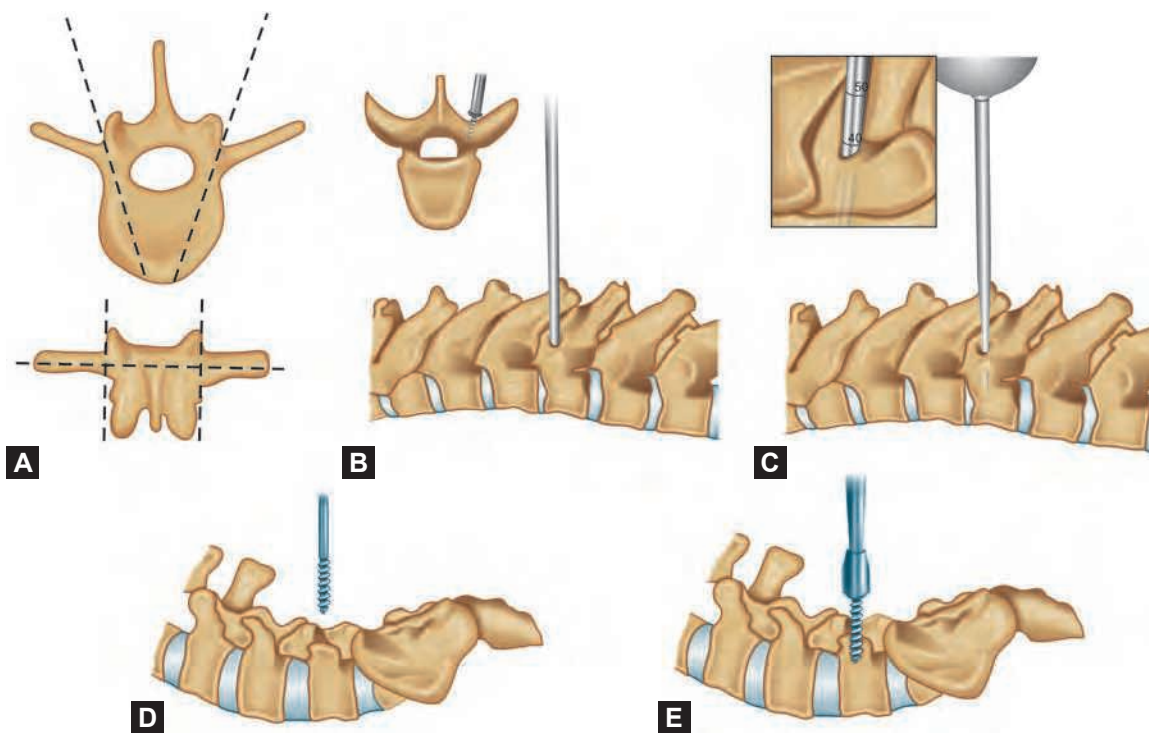
SURGICAL TECHNIQUE

After exposing the posterior elements, the starting point for a pedicle screw is generally located at the junction of a vertical line running along the lateral aspect of the facet joint (or alternatively the lateral border of the pars interarticularis) and a line drawn horizontally through the middle of the transverse process (Fig. 67.2A). Fluoroscopy or surgical navigation systems may also be employed to verify trajectory. In a meta-analysis assessing a total of 7,533 pedicle screws, computed tomography (CT)-based in vivo navigation systems gave rise to 90.76% accuracy versus 85.48% for conventional fluoroscopy.²³ In another cadaveric study, the combination of CT navigation and verification using a ball-tipped probe was 98% sensitive and 80% specific in the lumbosacral spine.²⁴ Nevertheless, the benefits of this

technology must be weighed against increases in cost and radiation exposure to the patient and surgeon alike.

Once the entry site has been identified, a cortical window is created using a high-speed bur or an awl (Fig. 67.2B). A pedicle probe is then used to develop an appropriate path for the screw that should be approximately parallel to the superior endplate of the vertebral body in the sagittal plane (Fig. 67.2C); the coronal trajectory will vary depending upon the level of the spine. At L1, the probe should be aimed approximately 10–15° obliquely across the pedicle and this angulation will increase 5° at each caudal level so that at S1 the trajectory should be 25° medial and 10° inferior. The pedicle finder is typically inserted to a depth of 35–40 mm and care should be taken not to penetrate the cortices of the pedicle or the ventral vertebral body. The pedicle probe is removed and a ball-tipped probe is passed along the tract to ensure there are no cortical violations. In dense bone, a tap may be used to optimize screw purchase although this may not be necessary in patients with osteoporosis (Fig. 67.2D).

Prior to insertion of the screw, the pedicle is palpated with a ball tip probe once again. Sedory et al. tested this



Figs. 67.2A to E: Lumbar pedicle screw insertion technique. (A) The starting site of a typical lumbar pedicle screw is at the intersection of a line drawn through the lateral border of the facet and a line drawn horizontally through the transverse process. (B) A high speed bur is used to break the cortex. (C) A pedicle finder is inserted to create a path for the screw and the screw is appropriately measured. (D) A tap is inserted to optimize screw purchase. (E) The appropriate size screw is inserted.

technique in cadavers and showed that it was 81% accurate for confirming the integrity of intact pedicles but was much less reliable for determining the exact location of a breach. The authors concluded that sounding the pedicle with a ball-tipped probe alone may be insufficient for detecting a cortical defect and should therefore be used with caution.²⁵

After the continuity of the tract has been confirmed, an appropriately sized screw is then selected and inserted across the pedicle into the vertebral body (Fig. 67.2E). In general, the largest diameter screw that is able to be safely accommodated by the pedicle should be used to maximize purchase. An *in vitro* study by Brantley et al. demonstrated increased fixation stiffness if the screw fills the pedicle by 70% or more, or penetrates the vertebral body by >80%.²⁶ As discussed previously, pedicle length and diameter may vary depending upon the vertebral level and individual anatomy so it is obviously important to review the preoperative imaging studies and pay careful attention to tactile cues while placing screws.

COMPLICATIONS

Lumbar pedicle screw fixation can be technically challenging that may entail a steep learning curve. While the overall complication rate including all potential hazards is not insignificant, most of these adverse events are not considered to be severe. Jutte and Castelein retrospectively evaluated 105 consecutive lumbar or lumbosacral fusion cases supplemented with pedicle screws and noted a complication rate of 54%.²⁷ In the series of Whitecloud et al. consisting of 40 patients who underwent spinal fusion using a variable plating system, the incidence of all adverse events was found to be 45% that increased to 63% with reoperations.²⁸ In their review of 617 fusions, Esses et al. reported intraoperative and overall complication rates of 9.6% and 27%, respectively.²⁹

Fortunately, neurologic injury arising as a result of pedicle screw placement is a rare occurrence. Davne and Myers observed neurologic complications in only 1.1% of 486 instrumented lumbar fusion cases with a 0.4% incidence of nerve injury due to screws breaching the pedicle.³⁰ In a meta-analysis of 35,630 pedicle screws, Gautschi et al. reported the rates of dural punctures and root irritation to be <0.20%.³¹

Even though the risk of neurologic injury is relatively low, intraoperative neurophysiologic monitoring during lumbar spinal surgery has become more prevalent,

especially with the emergence of minimally invasive techniques.³² In an animal model, screws associated with a cortical defect exhibited significantly lower evoked potentials compared to those within intact pedicles.³³ In a prospective study of 90 lumbar fusion cases employing transpedicular fixation, Glassman et al. showed that the utilization of intraoperative electromyographic stimulation to assess the accuracy of screw placement was 98% effective as verified by postoperative CT scans.³⁴ Nevertheless, routine intraoperative neurophysiologic monitoring is not universally accepted as the “standard of care” for these procedures because detractors insist that there is still no definitive evidence indicating that these adjunctive modalities actually improve patient outcomes.³²

With instrumentation becoming more common in the lumbar spine, the incidence of surgical site infections has increased as well. In a case series involving thoracolumbar fractures stabilized with pedicle screw constructs, the overall infection rate was 10% but individuals with neurologic injuries appeared to be at greatest risk.³⁵ In contrast, the prevalence of infection appears to be lower with elective surgeries where the published rates have ranged from 0.8% to 4.7%.^{27,29,36,37}

In the presence of a documented infection requiring formal irrigation and debridement, it is generally recommended that the instrumentation be left in place unless it has loosened or failed in order to maintain spinal stability and avoid any loss of correction or progressive deformity indicative of a nonunion.³⁸⁻⁴⁰ However, in many instances these individuals may require multiple surgical procedures to address their infections. Ho et al. retrospectively reviewed 53 pediatric patients who developed postoperative infections after posterior spinal fusion procedures for scoliosis and found that 47% of these cases in which the implants were retained hardware necessitated serial debridements.⁴¹ In a prospective study of 13 patients with deep wound infections whose pedicle screws were not removed during a subsequent reoperation, there were no significant differences in outcomes compared to a control group with no history of infection at an average follow-up of 22 months.⁴² Even though there is some evidence suggesting that lumbar instrumentation may not need to be removed in the setting of a postoperative infection, the surgeon must still weigh the risk and benefits of retaining the hardware in these situations. It has been shown that titanium instrumentation is less susceptible to biofilm adherence that is known to play a role in long-term colonization;^{43,44} this inherent resistance of titanium is one

reason why it has become the biomaterial of choice for spinal instrumentation.

Fixation failure is another well-recognized complication of pedicle screws. In the previously cited review of Gautschi et al. the rate of screw pullout ranged between 2% and 7.5%.³¹ As discussed in the preceding section, the biomechanical profile of these implanted is affected by both bone quality and screw design but correct screw placement may also decrease the stresses applied to the pedicle. Youssef et al. showed that screws directed more cephalad as opposed to caudal or parallel to the superior endplate resulted in a greater mean bending moment across the pedicle.⁴⁵ A number of different salvage methods have been described such as cement augmentation, reintroduction of a larger diameter pedicle screw, adding supplemental instrumentation (i.e. laminar hooks), or extending the fusion that significantly decreases segmental motion across any levels of suboptimal fixation.²⁰ When revising a failed construct, Gautschi et al. stated that restoring sagittal balance is “mandatory to prevent new screw pullout.”³¹

Other complications associated with the use of pedicle screws in the lumbar spine include hardware prominence that may even necessitate implant removal, particularly in thin individuals. Finally, transpedicular fixation may contribute to the development of adjacent level degeneration if the screws impinge on the facet joint of a vertebra that is not intended to be incorporated into the arthrodesis.¹²

MINIMALLY INVASIVE TECHNIQUES OF LUMBAR PEDICLE SCREW INSERTION

Less invasive techniques of lumbar fusion have gained in popularity in recent years. The technique of percutaneous pedicle screw insertion in the lumbar spine was first described by Magerl in 1984 with the pedicle screws connected to an external fixation device.⁴⁶ Lowery and Kulkarni described a technique for posterior lumbar internal fixation using percutaneous technique with the insertion of rods and connectors to supplement anterior lumbar interbody fusion. In a case series of 86 patients undergoing lumbar interbody fusion with this technique the authors reported a 96% successful fusion rate.⁴⁷

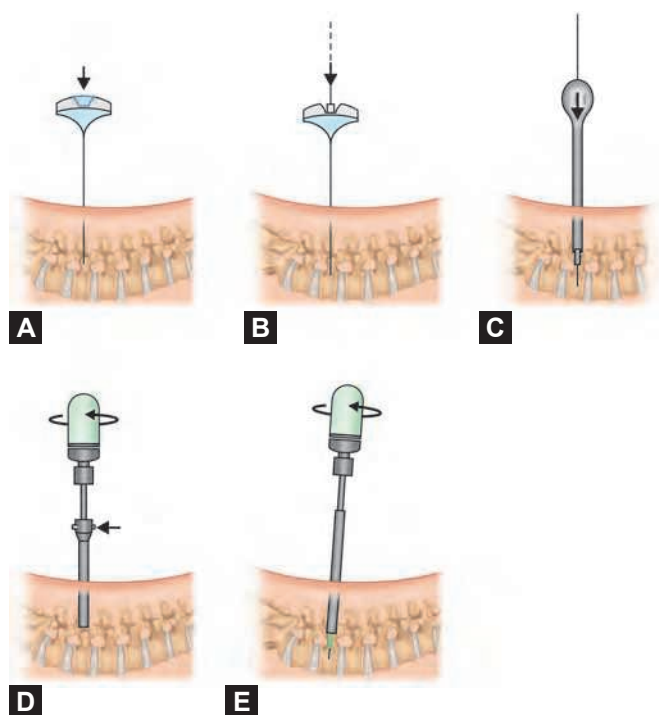
The goals of minimally invasive techniques are to decrease postoperative pain and shorten recovery time by eliminating soft tissue disruption caused by excessive dissection and prolonged skin and muscle retraction. Percutaneous techniques potentially reduce trauma to the two

main posterior spinal muscle groups, which are the deep paramedian transversospinalis muscle group and the erector spinae muscles. These muscles run along the thoracolumbar spine and contribute to dynamic stability of the spine. Preservation of these muscles has been shown to increase lumbar extension strength by >50%.⁴⁸ It has also been hypothesized that the maintenance of physiologic motion by preserving these paraspinal muscle groups can prevent adjacent segment degeneration, although to date this has not been shown clinically.⁴⁹

As a whole, minimally invasive techniques in the lumbar spine have been shown to be cost effective. In a review of prospectively collected registry data, Lucio et al. looked at 101 patients treated with open lumbar interbody fusion compared to 109 patients treated with minimally invasive spine surgery for stenosis with instability. Mean total hospital costs in the open group were \$27,055.53 and \$24,320.16 for the minimally invasive group. There were also more complications and adverse events (including deep vein thrombosis, emergency room admissions, hospital readmissions, reoperations, etc.) in the open group compared to the minimally invasive group.⁵⁰

Percutaneous pedicle screws are typically cannulated and placed over a guide wire. Intraoperative fluoroscopic guidance is utilized. Incisions are made lateral to the midline to allow for medial trajectory of the screw. A Jamshidi needle is used to locate the starting site of the pedicle, and is subsequently advanced through the pedicle and into the vertebral body (Fig. 67.3A). After removal of the trocar, a guide wire is passed through the needle and advanced into the vertebral body (Fig. 67.3B). The Jamshidi needle is then removed and a series of dilators is passed over the guide wire to create a working portal through the paraspinal muscles (Fig. 67.3C). A tap is then inserted over the guide wire, which can be calibrated to the dilator in order to measure screw length (Fig. 67.3D). A pedicle screw is then inserted over the guide wire (Fig. 67.3E).⁵¹

Minimally invasive systems are available for posterolateral fusion and transforaminal lumbar interbody fusions (TLIFs) as well. Using tubular retractors or a paraspinal muscle splitting approach, the transverse process and the facet joint can be exposed for bone graft and pedicle screw insertion with minimal muscle stripping. Once the surgical field is established, the remainder of the procedure may be performed under loupe magnification or with an operating microscope. Connecting rods can also be inserted through small stab incisions.^{49,52}



Figs. 67.3A to E: Percutaneous lumbar pedicle screw insertion technique. (A) A Jamshidi needle is used to locate the lumbar pedicle and is inserted into the vertebral body. (B) A guidewire is inserted through the needle. (C) A series of dilators is passed over the guidewire to create a working portal. (D) A tap is inserted over the guidewire to create a path for the pedicle screw. (E) A pedicle screw is inserted over the guidewire.

Mid-term clinical outcomes of less invasive lumbar fusion using percutaneous pedicle screws have been promising. Foley and Gupta performed a clinical trial of 12 patients undergoing either a one or two level fusion using a percutaneous tubular retractor system. At an average follow-up of 13.8 months, the authors reported excellent results in six patients, good results in five, and poor results in one.⁵³ In a case series of 29 consecutive patients undergoing posterolateral fusion with percutaneous techniques for symptomatic spondylolisthesis, Harris et al. reported outcomes that were comparable to prior studies using open techniques at 12 months follow-up.⁵⁴ In a retrospective review of 80 patients undergoing single level decompression and posterolateral fusion, 37 of which were minimally invasive and 43 of which were open, Kotani et al. showed that, at 2 years follow-up, the minimally invasive approach reduced low back pain and improved functional activities of daily living compared to the open technique.⁵⁵

Pedicle breach and neurologic injury with the percutaneous technique has been well studied and rates have

shown to be comparable with the open technique. Smith et al., in a study of 151 patients undergoing TLIF with placement of 601 total percutaneous pedicle screws under fluoroscopic guidance, reported a pedicle breach rate of 6.8% with only 2 screws causing neurologic symptoms.⁵⁶ In a retrospective review of 424 percutaneously inserted pedicle screws in the thoracolumbar spine in 88 patients, Raley et al. reported a 9.7% rate of misplaced pedicle screws with only one misplaced screw causing neurological symptoms.⁵⁷

Violation of the facet capsule during pedicle screw insertion can result in a significant amount of postoperative back pain. Although the rates of pedicle breach with the percutaneous technique are comparable to the open technique, rates of facet violation have been shown to be higher. In a cadaveric study by Patel et al. involving the insertion of 48 percutaneous pedicle screws by experienced surgeons under fluoroscopic guidance, they reported a 58% rate of facet violation. The authors went on to classify the violation type, which could be useful in future studies to determine the clinical significance of these facet violations.⁵⁸

The minimally invasive technique for pedicle screw insertion in the lumbar spine is a promising approach to treatment of both traumatic and degenerative conditions of the lumbar spine. The benefits of this technique, which are decreased blood loss, decreased postoperative pain, and earlier functional recovery post operatively, must be weighed against the limitations of this technique that are increased operating times, greater radiation exposure to the patient and operating room staff and, as highlighted above, the potential for facet joint violations. These techniques are also associated with a steep learning curve that the surgeon must overcome in order for patients to reap the benefits of the minimally invasive approach.

KEY CONCEPTS

- Lumbar pedicle screws have become the standard as a means for providing internal fixation in the lumbar spine.
- It is important to understand the anatomy of individual pedicles within the lumbar spine as the pedicles change in diameter, take on a more caudal and medial trajectory as one goes cephalad to caudad.
- Intraoperative navigation techniques including two-dimensional fluoroscopy and CT have been shown to increase the accuracy of pedicle screw insertion while minimizing potential of pedicle breach.

- Complications resulting from lumbar pedicle insertion, which include neurological injury, infection, and pedicle breach or fracture, occur at relatively low rates.
- Percutaneous techniques for the insertion of lumbar pedicle screws have the potential to substantially decrease postoperative pain, allow for earlier return to function, decrease hospital stay, and ultimately reduce the overall surgical cost; however, these benefits must be weighed against the limitations of a steep learning curve, longer operative time, and a reported increased rate of facet violations.

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Transfacet, Translaminar, and Cortical Screw Fixation of the Lumbar Spine

Kushagra Verma, Jeffrey Rihn, Alexander R Vaccaro

Snapshot

- » Transfacet Screw Fixation
- » Adjunctive Transfacet Fixation
- » Translaminar Screw Fixation
- » Adjunctive Translaminar Fixation
- » Cortical Screw Fixation

INTRODUCTION

Posterior lumbar fixation has been used in conjunction with bone grafting techniques to achieve bony fusion.¹ The probability of achieving a bony fusion is improved with rigid fixation. Pedicle screw (PS) fixation in the lumbar spine remains the good standard for rigid fixation.^{2,3} Its long-standing use also underscores its biomechanical strength and efficacy in providing a rigid construct for an arthrodesis. However, utilization of PS fixation often necessitates a wide posterior exposure with soft tissue dissection and disruption of a portion of the facet joint. In addition, the ease of insertion and safety has been debated for several years.⁴⁻⁶ Lonstein et al. reported a 2.4% incidence of misplaced PSs and a 23–24% incidence of late-onset discomfort related to screw placement or a pseudarthrosis. Overall, the safety and accuracy of PS fixation has improved in the thoracic and lumbar spine using a free-hand technique, advanced imaging, or even navigation in the revision setting.⁷⁻¹⁰ Of note, misplacement of PSs is more common in the thoracic spine, but rarely leads to neurologic or vascular compromise.¹¹

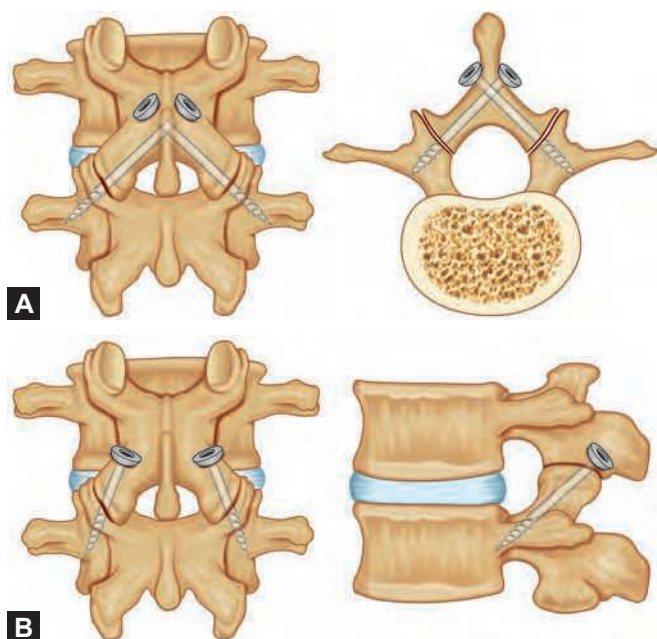
To avoid the risks associated with PS fixation in the lumbar spine, alternative means of posterior lumbar fixation have been developed. Advocates for these fixation options cite less soft tissue dissection, minimized disruption to the adjacent facet joint capsule, decreased neurologic risk, decreased implant cost, and a minimally

invasive approach, with comparable results compared to PS systems.¹² Less rigid facet screw fixation systems also allow for implant-host load sharing and increased micro-motion, which may promote a biological fusion.¹³ However, excessive motion may also lead to a pseudarthrosis and early hardware failure. The fixation options discussed in this chapter include ipsilateral transfacet fixation, translaminar facet fixation, and cortical screw (CS) fixation. Landmark anatomic, biomechanical, and clinical outcome studies describing the technical placement and efficacy of these fixation options are reviewed.

TRANSFACET SCREW FIXATION

Ipsilateral lumbar transfacet screw (TFS) fixation was first described by King in 1948.¹⁴ Later, this was method of fixation modified by Boucher in 1959 to help achieve fusion in the lumbosacral spine using screws placed across the facet joints.^{15,16} The original descriptions of TFS placement were made through the ipsilateral lamina across the facet joint (Fig. 68.1B). Techniques were later developed to place facet fixation from the contralateral lamina (Fig. 68.1A).¹⁷ The terminology regarding these differing techniques at times has been not clearly defined.

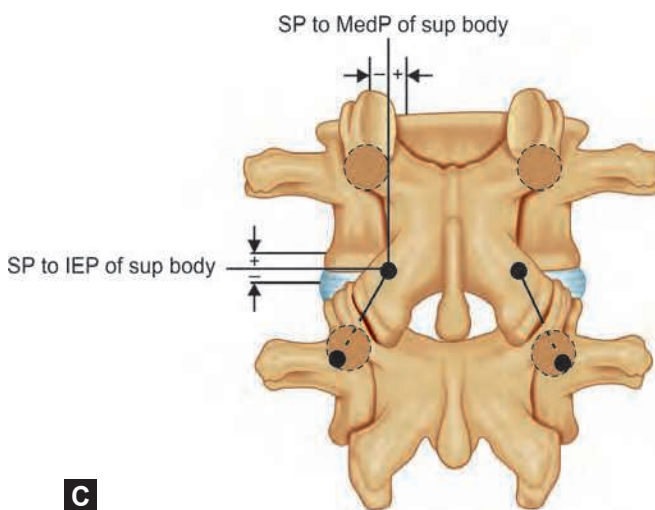
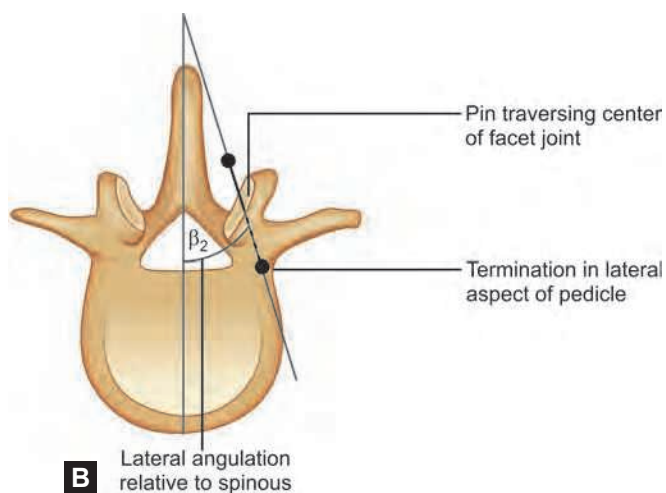
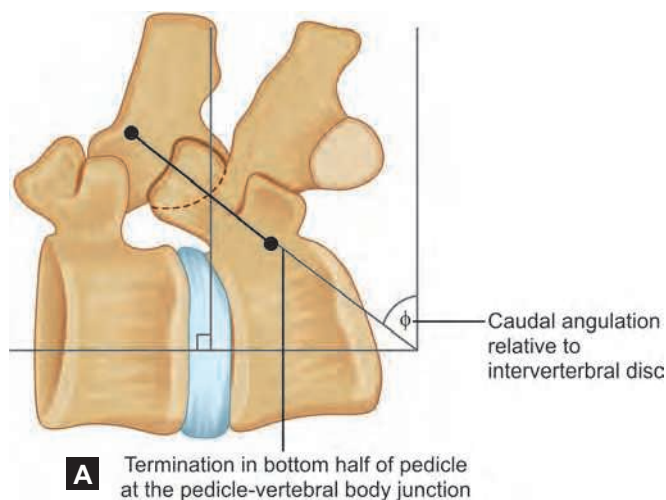
In an anatomic and radiographic analysis, Su et al. described the anatomy of the superior and inferior articulating processes for the L2 to S1 levels.¹⁸ These anatomical relationships were confirmed by a magnetic resonance



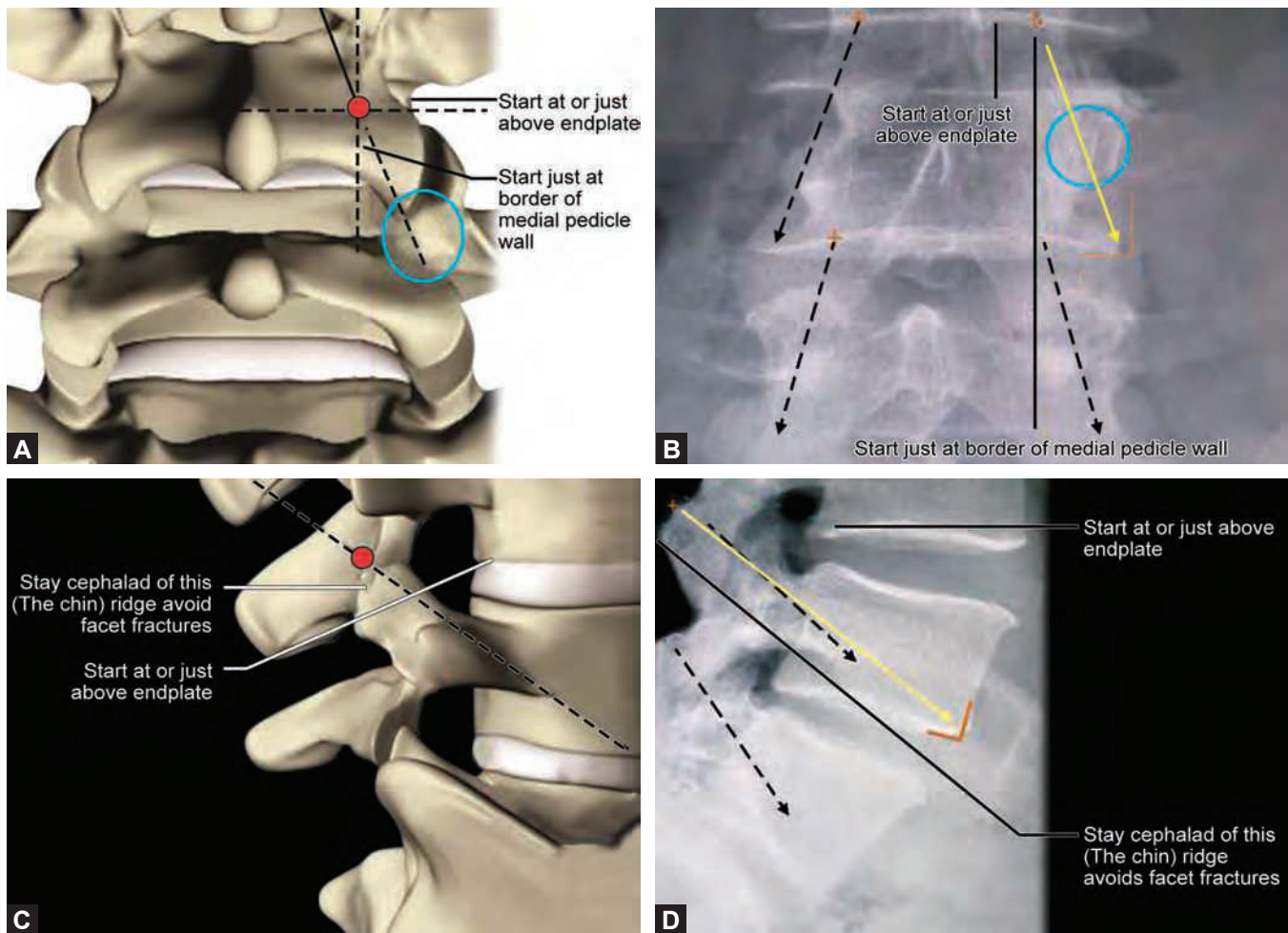
Figs. 68.1A and B: (A) Illustration of transfacet screw fixation from the contralateral lamina. (B) Illustration of transfacet screw fixation from the ipsilateral lamina.

imaging (MRI) study in 100 normal children.¹⁹ By placing pins in cadaveric specimens, the authors were able to identify the screw length, screw trajectory in the sagittal (ϕ , Fig. 68.2A), and axial planes (β_2 , Fig. 68.2B), as well as the ideal starting point for the L3-S1 levels (Fig. 68.2C). Due to the vertical orientation of the facet joint at L2-L3, this level was not amenable to an ipsilateral TFS. In the sagittal plane, the screw should be directed towards the inferior half of the inferior segment with a caudal angulation (ϕ) of 26° at L3-L4, 29° at L4-L5, and 31° at L5-S1. This angle is measured relative to intervertebral disc. For the axial plane, the screw should be laterally angulated 14.6° at L3-L4, 15.3° at L4-L5, and 17.6° at L5-S1. The starting point in the cephalad caudal plane lies at the inferior end plate, while in the medial lateral plane is within 1 mm of the medial wall of the pedicle.¹⁸ Overall, the direction of the screw has been generalized to be “down and outward.”¹³

Chin et al.²⁰ recently described a transfacet PS at L4-L5 in which the traditional TFS technique is modified such that the screw traverses both the facet joint and the pedicle ending in the vertebral body of the caudal level. Anatomically, the start point is once again at the medial pedicle wall and the inferior end plate of the proximal vertebral body (Figs. 68.3A to D). After a midline incision and exposure of the L4 lamina, A Jamshidi needle is placed



Figs. 68.2A to C: For transfacet screw fixation, these figures show the caudal angulation relative to the intervertebral disc (A), the lateral angulation relative to the spinous process (B), and the start point (C).



Figs. 68.3A to D: These figures show once again the start point for the TFS technique on an illustrated model and radiographic view in the coronal (A and B) plane and sagittal (C and D) plane.

on the L4 lamina just medial to the inferior facet. After confirming anteroposterior (AP) and lateral trajectory with via fluoroscopy, a mallet was used to drive the needle in a caudal and lateral direction. Correct position is confirmed with imaging after which a 5.5×50 mm cannulated screw placed.²⁰

ADJUNCTIVE TRANSFACET FIXATION

Published non-union rates for anterior lumbar interbody fusion (ALIF) procedures in the lumbar spine may be as high as 24%.²¹⁻²³ In part, these results have been the impetus for augmenting ALIF instrumentation with additional posterior fixation to improve rigidity. While PS systems in the lumbar spine remain the gold standard for posterior spinal fusions largely due to their biomechanical strength, over the last few years there have been numerous

biomechanical studies reporting on the efficacy of ipsilateral TFS as an augment to ALIF or lateral interbody fusion techniques.²⁴⁻²⁶

Volkman et al. was one of the first to show that posterior TFS fixation improved construct stiffness in compression and extension after ALIF in a cadaveric model.¹² In another biomechanical study, Mahar et al. compared a percutaneous 4.5 mm TFS system with 5.5 mm PS when used with an anterior cage with a compression load cells. The TFS allowed for screw length measurements and compression across the facet joints. The trajectory of screws was also modified slightly from Boucher to obtain purchase with the pedicles of the inferior vertebral body.¹⁵ The author reported no differences between groups in stiffness or load fluctuation with flexion, extension, lateral bending, and torsion of the L4-L5 cadaver specimens.

Ferrara et al.¹³ assessed the relative efficacy of TFS (4.5 mm × 40 mm, lag screws) and PS systems (6.5 mm × 45 mm, fully threaded screw with 6.5 mm titanium rod) with short- and long-term repetitive cycling. In short-term testing, both screw systems showed equivalent stiffness and range of motion (ROM) when used in conjunction with an anterior device. Long-term testing (180,000 cycles, 6 weeks) showed 1°–3° of residual motion that remained constant for the testing period and equivalent between groups. In a cadaver study of L4–L5 vertebrae, Agarwala et al. showed that TFS had similar rigidity to bilateral PS in flexion-extension. In axial rotation and lateral bending, TFS offered less rigidity than PS systems when used in isolation. The differences, however, were minimal when posterior fixation was used as an adjunct to anterior column support.²⁷ Kretzer et al. did a similar cadaveric study for lateral interbody arthrodesis and found no differences in ROM at L2–L3 and L4–L5 for isolated lateral cage, lateral cage + TFS, and lateral cage + bilateral PS.²⁶ Overall, these studies suggest that transfacet fixation is comparable to PS fixation when used in conjunction with an anterior or lateral interbody cage. Pedicle screw systems remain biomechanically superior, however, when used in isolation.

In a clinical study, Voyadzis and Anaizi described the technique of TFS fixation in 10 patients also undergoing an extreme lateral interbody fusion. The authors report safe and effective percutaneous transfacet fixation in the lateral decubitus position at L3–L4 and at L4–L5, with utilization of a midline incision centered over the spinous process. Using image guidance for localization, the starting point for the screw was confirmed with a Jamshidi needle at the inferior end plate and midpoint of the pedicle. As described above, Kirschner wires were driven through the facet joint with a 30° caudal and 15° trajectory after which a cannulated screw is placed. The author noted that TFS—as opposed to PS fixation—reduced operative time and surgical morbidity in select cases. Mean operative time was under 3 hours, blood loss <30 mL, with mean hospital stay under 48 hours.²⁸

■ TRANSLAMINAR SCREW FIXATION

Placement of translaminar screw (TLS) fixation requires that 4.5-mm CSs are inserted from each side of the spinous process of the upper vertebra. These screws are passed through the lamina across the facet joints and end at the transverse process of the contralateral lower vertebra (Aepli et al. 2009).²⁹ Early clinical results and a technique for TLS was described by Jacobs et al.³⁰ in 1989 using a 4.5-mm

screw of approximately 50 mm in length. Results from 43 patients demonstrated a 91% fusion rate with 93% clinical improvement in axial back pain at 6 months.³¹ Aepli et al. reported 10-year follow-up data from 643 patients treated with TLS fixation for a variety of diagnoses. Overall, 74% of patients reported a good outcome with 92% of patients reporting a good outcome if the preoperative disc height was <80% of normal. The authors suggested that preoperative disc collapse resulted in less segmental motion and was protective against a pseudarthrosis. Interestingly, there was also a trend towards improved outcomes in patients with degenerative spondylolisthesis rather than degenerative spondylarthrosis.²⁹

■ ADJUNCTIVE TRANSLAMINAR FIXATION

A majority of biomechanical studies have focused on the use of TLS fixation in conjunction with anterior cages. Phillips et al. demonstrated that ALIF cages at L5–S1 have the greatest angular motion and least compressive preload under extension. When ALIF cages were supplemented with TLS, the angular motion was significantly reduced in extension compared with cages alone or the intact spine.³¹ Harris et al. showed that a one-level transforaminal lumbar interbody fusion (TLIF) with a cage did not increase overall spine flexibility, but did result in increased axial rotation at L4–L5. When used as an augment, bilateral PS increased stiffness the most followed by unilateral PS, then unilateral TLS.³² In contrast, Razi et al. found no differences in ROM when either TFS or PS was used in conjunction with a femoral ring allograft in cadaveric study.³³

For two-level ALIF, Eskander et al. reported that either PS or TLS decreased in flexion and, to a smaller degree rotation when compared to an intact spine. However, there was no difference between instrumented and non-instrumented spines in extension. Overall, there was a tendency towards increased stiffness with pedicle versus TLSs, but the difference was not statistically significant.³⁴

In contrast, Zhan and Tian showed two-level posterior augmentation of ALIF cages improved stiffness compared to the intact spine or anterior instrumentation. The type of posterior fixation—PS versus TLS—did not affect outcome.²⁴ Similarly, Hou et al. found anterior cages used for two-level fusions augmented with either TLS or PS had increased stiffness as compared to an intact spine or ALIF cages alone. However, there was no difference between in stiffness, ROM, or adjacent disc pressure for TLS versus PS.²⁵

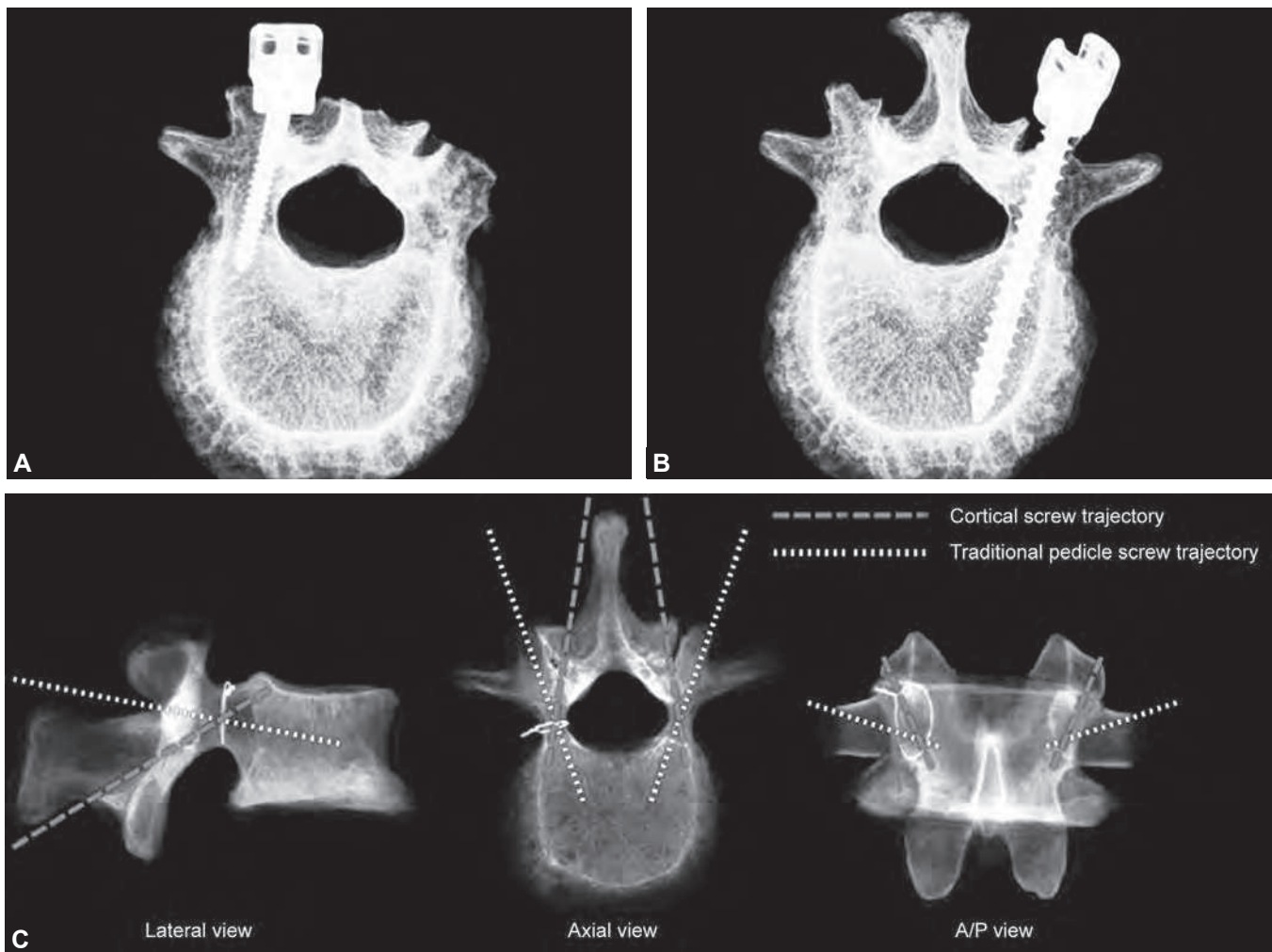
Kang et al. described a similar computed tomography (CT)-based percutaneous technique in patients for adjunctive fixation after an ALIF. The procedure was performed under conscious sedation, was an average duration of 43 minutes, and resulted in a successful fusion in all 17 patients.²³ Overall, either open or percutaneous TFS fixation safely improves construct stiffness in extension and axial rotation at one or two-levels, but nonetheless remains biomechanically inferior to PS.

CORTICAL SCREW FIXATION

Santoni et al. proposed a CS as a potential modification to the traditional anatomic PS trajectory. The CS has a more medial starting point with a trajectory that follows a caudocephalad path in the sagittal plane and a more lateral direction in the axial plane (Figs. 68.4A to C).

Instead of engaging trabecular bone within the vertebral body, the CS is secured by cortical bone from the pedicle and is anchored within the pars interarticularis. Lastly, unlike PS fixation, CS fixation requires interconnecting rods fastened with top-locking connectors.^{35,36}

Although the emerging technique requires a shorter screw (average 29 mm) with a smaller diameter (average 4.66 mm), Santoni et al. reported a trend ($p = 0.08$) towards 30% greater pullout strength for CS versus PS.³⁵ Of note, 20% of CSs placed had a breach of the medial wall of the pedicle seen on plain radiography and gross examination. In addition, the study offered limited information regarding the screw insertion technique. Perez-Orribo et al. recently published the first cadaver study to assess the segmental ROM of CS (4.5 mm) versus PS (6.5 mm) in an intact spine, in conjunction with a TLIF, and in association



Figs. 68.4A to C: These figures illustrate the cortical screw trajectory in the axial plane (A and B) and other planes (C).

with a direct lateral interbody fusion (DLIF). For an intact spine or a non-stabilizing TLIF, a traditional PS-rod system had slightly greater stiffness in axial rotation and lateral bending than CS-rod systems. However, CS systems may offer greater rigidity in flexion-extension. In conjunction with a DLIF, there were no significant differences in ROM between PS and CS.

Cortical screw fixation is postulated to become a clinically useful option to improve pull out strength in osteoporotic bone and has the advantage of less soft tissue dissection than PS systems. However, the more medial starting point and potential for medial pedicle wall violation may limit the utility of this technique. To date, minimal data is available in terms of a safe screw insertion technique that avoids medial pedicle wall violation. In addition, no studies have reported clinical results using this technique.

Pedicle screw fixation of the lumbar spine remains the gold standard for achieving rigid fixation from a posterior approach. While generally biomechanically inferior when used in isolation, transfacet, translaminar, and newly described CSs may offer a useful alternative for posterior fixation. These fixation options minimize soft tissue dissection, may reduce the risk of nerve root injury, and are undoubtedly cost advantageous. Biomechanical strength of alternative fixation constructs versus PS systems may be relatively similar when these systems are utilized as an adjunct after anterior or lateral interbody fusion cages. Clinical outcome data, however, remains limited.

KEY POINTS

- Pedicle screw fixation of the lumbar spine remains the gold standard for achieving rigid fixation from a posterior approach.
- Transfacet, translaminar, and CSs offer an alternative for posterior fixation.
- Alternative fixation techniques minimize soft tissue dissection, risk to adjacent nerve roots, and implant costs.
- Transfacet, translaminar, and CSs may be biomechanically similar to PSs when used as an adjunct to interbody fusion devices.
- To date, clinical outcome data remains limited.

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Anterior Lumbar Interbody Fusion

Ning Lu, Yan Wang, Andrew P White

Snapshot

- » History of Anterior Lumbar Interbody Fusion
- » Surgical Anatomy
- » Indications for Anterior Lumbar Interbody Fusion
- » Controversies Related to Anterior Lumbar Interbody Fusion
- » Complications
- » Applications of Anterior Lumbar Interbody Fusion in Revision Surgery
- » Innovations Related to Anterior Lumbar Interbody Fusion

HISTORY OF ANTERIOR LUMBAR INTERBODY FUSION

The first published description of an interbody fusion was the anterior lumbar interbody fusion (ALIF). Muller¹ is credited with this first use of ALIF, as a treatment for Pott's disease, in 1906. Capener² and Mercer³ subsequently adopted it for the treatment of spondylolisthesis. In 1933, Burns⁴ performed an interbody fusion for a traumatic L5-S1 spondylolisthesis via a transabdominal approach. None of these pioneering authors discussed intervertebral disc degeneration as an indication for performing ALIF.

Lane and Moore⁵ were the first authors to describe ALIF as a treatment for degenerative disease. Their 1948 publication is regarded as the first endeavor to popularize this procedure to treat symptoms attributable to lumbar intervertebral disc degeneration. Soon thereafter, in 1953, Cloward⁶ reported the outcomes of 262 patients with disc degeneration, sciatica, and back pain, who were treated with ALIF. Others continued to use the anterior approach for surgical treatment of lumbar tuberculosis, intervertebral disc degeneration, and spondylolisthesis during the 1950s and the 1960s, but the number of cases reported by surgeons was small.

Reports of the use of spinal instrumentation for anterior lumbar stabilization soon followed. Humphries et al.⁷ described an anterior lumbar compression plate with

unicortical screw fixation in 1961. While the early results were outstanding, subsequent authors reported less favorable results. For example, Stauffer and Coventry⁸ reviewed the Mayo Clinic experience and found a 56% overall "success" rate. This modest rate of success was not felt to justify the invasive nature of the procedure. For this reason, ALIF lost favor until the advent of cylindrical fusion cage in the 1980s.

In recent decades, ALIF has gained popularity. This is related, in part, to the proposed advantages of ALIF over posterior fusion. These include provision of a large fusion surface area, restoration of segmental height and alignment, and avoidance of damage to the posterior paraspinal musculature. In concert with the increase in ALIF use, novel implants were developed. The instrumentation used for the application of these implants was well designed and was typically "user friendly". These implants were used for a variety of indications by enthusiastic surgeons in what has been termed "the age of the cage". Spectacular results were initially reported.

In the early 1990s, minimally invasive lumbar spine surgery, intended to minimize soft-tissue damage, was introduced when the first laparoscopic lumbar discectomy was described by Obenchain in 1991.⁹ Laparoscopic ALIF was described in 1995 by Zucherman and colleagues.^{10,11} This technique, initially embraced with enthusiasm, was found to be technically challenging and has since been

replaced by mini-open techniques. Mini-open ALIF is typically performed through a small para-median abdominal incision, with dissection around the rectus abdominis muscle to access the retroperitoneal space. In 1997, Mayer¹² described the modified retroperitoneal and transperitoneal approaches to ALIF using microsurgical instruments. He concluded that these techniques are reasonably applicable from L2 to S1.

In some clinical scenarios, ALIF can be an adequate treatment, without posterior stabilization. It has been recognized, however, that this “stand-alone” strategy can be associated with a high rate of nonunion.^{13,14} For this reason, and also since there is biomechanical evidence to suggest that many ALIF cages do not provide adequate stability,¹⁵⁻¹⁷ several types of supplementary fixation have been introduced. These have included anterior plates, pedicle screws, facet screws, and translaminar screws.¹⁸⁻²² While ALIF is typically performed as part of a circumferential fusion, there is conflicting information regarding the potential benefit of the addition of posterior surgery. At least one modern clinical study evaluating stand-alone ALIF has shown suboptimal radiographic and clinical outcomes; the author suggested that additional benefit may be gained from adjunctive posterior stabilization.²³ Another prospective cohort study, however, concluded that stand-alone ALIF leads to better clinical results than anteroposterior lumbar fusion (APLF) in the treatment of degenerative disc disease.²⁴ Currently, it is unclear whether stand-alone cages are sufficient for ALIF and there is no consensus as to what degree of stability is required to guarantee a satisfactory clinical outcome.

SURGICAL ANATOMY

The anterior aspect of the lumbar spine is within the retroperitoneal space, dorsal to the abdominal cavity and its contents.^{25,26} The peritoneum contains the descending colon, kidney, and ureter. The visceral organs can typically be safely retracted without opening the peritoneum. The dome-shaped roof of the abdominal cavity is the thoracic diaphragm (a thin sheet of muscle under the lungs). The diaphragm bridges over the psoas and quadratus lumborum by the arcuate ligaments. The left crus of the diaphragm extends to the second lumbar vertebra, and attaches to the anterior longitudinal ligament.

The psoas occupies the space lateral to the lumbar vertebral bodies. Within the psoas lie the branches of the

lumbosacral plexus. The genitofemoral nerve lies on the ventral surface of the distal psoas belly. The nerve roots giving rise to the femoral nerve are found in the substance of the muscle, typically descending within the lateral aspect of the psoas in the lower lumbar region. The obturator nerve will be found along the medial edge of the psoas. The lateral femoral cutaneous nerve will exit the upper edge of the psoas and can be seen passing into the pelvis.

The aorta descends into the abdomen anterior to the body of the last thoracic vertebra. The inferior vena cava arises from the major lower extremity veins, which are the common iliac veins. The inferior vena cava ascends alongside the vertebral column, typically on the right. The aorta and inferior vena cava typically bifurcate anterior to the fourth lumbar vertebra. Therefore, the common iliac artery and vein are encountered in the surgical approach to the fifth lumbar vertebra. Segmental vessels pass in the axial plane, around each vertebral body, and are intimately associated with the periosteum.

Surgical Approaches to the Anterior Lumbar Spine

Anterolateral Retroperitoneal Approach to the Lumbar Spine

The retroperitoneal approach²⁵⁻²⁸ is appropriate for access to the mid-lumbar spine (L2-L5). A left-sided approach is typically preferred since manipulation of the thin-walled inferior vena cava is associated with higher risk than manipulation of the abdominal aorta. Furthermore, liver retraction is obviated by a left-sided approach. This anterolateral retroperitoneal approach can provide broad exposure of the lumbar spine with less risk to the viscera, great vessels, and sympathetic plexus, as compared to the transperitoneal approach.

In anticipation of surgery, a bowel prep is recommended to decompress the colon. The patient is positioned in a right lateral decubitus position; the left side is rotated upward 60°. This position is maintained with bolsters under the left hip and under the left shoulder. The articulation in the operating table should be used to extend the thoracolumbar junction. By increasing the distance between the lower ribs and ilium, the depth of retraction is reduced. Retraction is also facilitated by left hip flexion, which relaxes the ipsilateral iliopsoas muscle,

while the right leg is typically extended. When possible, the patient should be positioned with the operative vertebral end plates orthogonal to the floor. This makes intraoperative radiographs easier to interpret and removes a dimensional variable in planning placement of instrumentation.

Intraoperative radiographs are used to plan the location of the skin incision. Superficially, the latissimus dorsi and posterior serratus inferior are incised. The external oblique fascia is then identified, and the muscle is opened in line with the skin incision to the lateral border of the rectus fascia. The internal oblique and transversus abdominis muscles are then opened. The iliocostal muscle is partially divided posteriorly. The transversalis fascia is incised to enter the retroperitoneal space. The peritoneum can then be dissected from the abdominal wall, thus exploring the retroperitoneal space. Dissection of the more medial muscle layers and fascia is more difficult, and peritoneal tears can occur. Tears in the peritoneum are typically repaired. Posteriorly the peritoneum is dissected free from the inferior pole of the left kidney and from the posterior abdominal wall. A plane between the retroperitoneal organs (kidney and ureter) and the retroperitoneal musculature (quadratus lumborum and iliopsoas) is developed with blunt dissection. The retroperitoneal organs and peritoneal sac are retracted medially and toward the dependent side. This exposure can then be maintained with a self-retaining, broad-based, table-mounted retraction system, such as the Bookwalter or Omni retractor system. Fluoroscopy or plain radiograph is used to confirm the appropriate spinal level.

The psoas muscle is mobilized posteriorly using a Cobb elevator to expose the anterolateral aspect of the operative vertebrae. Care is taken to avoid unnecessary mobilization or retraction of the psoas. The fibers of the psoas muscle should not be transected. Care should be taken to avoid damaging the lumbosacral plexus within the psoas muscle. Neurological structures on the surface of the muscle should also be treated with caution: the genitofemoral nerve, which provides sensation to the scrotum and inner thigh, can be typically identified on the ventral surface of the muscle distal to L2. Additionally, the sympathetic trunk can typically be identified along the medial border of the psoas muscle. Monopolar cautery should not be used in this area, to reduce the risk of injury to the sympathetic trunk.

Segmental vessels are identified as the neural foramina are approached. These vessels can be ligated midway between the parent vessel and the foramen; ligation at this point may reduce the risk of vascular compromise of the neural elements. After the segmental vessels are secured,

the aorta and iliac vessels are mobilized to expose the ventrolateral surface of the vertebral bodies. The intended spinal procedures can then be performed. After removing the retractors, inspecting the retroperitoneal space, and ensuring meticulous hemostasis, the peritoneal and retroperitoneal contents are allowed to fall back into normal anatomic position. The abdominal muscle layers are closed anatomically and the skin is closed in the standard fashion.

Anterolateral Approach to the Thoracolumbar Junction and the Upper Lumbar Spine

In cases where exposure of the thoracolumbar junction and the upper lumbar spine (L1 and L2) is desired, the skin incision is curved proximally. The incision should reach two rib interspaces above the corresponding operative vertebrae. This is most typically the 10th or 11th rib, in order to provide access to the thoracolumbar junction. A subperiosteal rib resection is performed, and the resulting aperture is widened using a rib spreader. Care should be taken to preserve the intercostal neurovascular structures, particularly with retraction of the upper rib. The diaphragm is identified and mobilized. Its attachments are released circumferentially from the crus to the peripheral costal attachments. A 2-cm cuff or diaphragm should be preserved for reconstruction during closure.

Once the retroperitoneum is entered, exposure of the upper lumbar segments can be achieved by retracting the lower pole of the kidney medially and superiorly. The ureter is carefully mobilized, and the left diaphragmatic crus, which extends to the second vertebral body, is taken down. Exposure of the vertebral bodies can then be performed. The psoas muscle is retracted posteriorly at L1 and L2; the degree of exposure is dictated by the goals of the surgery. Care is taken not to retract the psoas excessively. Injury to the psoas can cause lumbar plexus adverse events such as postoperative leg weakness, numbness, and pain. At closure, the diaphragm is carefully reattached to the costal margin. The crus is reattached as well. One or more chest tubes are employed, and a pleural seal is reestablished. The tissues of the thoracic wall are then closed in anatomic layers.

Midline Incision Approaches to the Anterior Lumbar Spine

When bilateral exposure of the lumbar spine is desired, a midline incision can be used to perform either a retroperitoneal or a transperitoneal approach.²⁵⁻²⁸

The patient is positioned supine with the sacrum elevated either by a bolster or by gently extending the operating table. This position helps to displace the abdominal contents rostrally, extend the distance between the lower ribs and ilium, and reduce the anticipated retraction distance from the skin to the vertebrae. Intraoperative fluoroscopy can be helpful with regard to positioning. The anteroposterior projection is used to confirm that the patient is not rotated. The lateral projection can be used to plan the location of the skin incision, and to determine the angle of approach to a particular disc space. Oxygen saturation is monitored in both legs during the perioperative period, with a pulse oximeter placed on the great toe of each foot.

A midline, left-sided paramedian, or Pfannenstiel incision can be used. A midline incision along the linea alba may reduce the risk of rectus muscle denervation, as the rectus muscle is approached medially and is retracted laterally. An incision above the umbilicus typically allows exposure of L4 and above while an incision below the umbilicus allows exposure of L4 to S1. An exposure of the L5-S1 disc generally requires an incision just above the superior aspect of the symphysis pubis. The rectus sheath is entered, and the left rectus muscle is retracted. The transversalis fascia is exposed, and the plane of retroperitoneal approach is entered. Electrocautery is used with caution to cauterize deep epigastric vessels during blunt retroperitoneal dissection. The peritoneal sac is manually dissected from the abdominal wall. The inferior aspect of the posterior rectus sheath can be incised to accommodate exposure of deeper structures. A table-mounted, self-retaining retractor system, such as a Bookwalter or Omni retractor, is used to maintain the exposure.

The L5-S1 disc space typically lies below the aortic bifurcation. The superior hypogastric plexus is at direct risk here however, since it lies directly anterior to the L5 vertebral body and the L5-S1 disc space. Injury to the plexus can cause retrograde ejaculation (RE) in male patients. In order to reduce this risk, the prevertebral tissues, including the superior hypogastric plexus, are carefully mobilized en bloc by blunt dissection over the disc space. Monopolar cautery should not be used here; bipolar electrocautery or vascular clips are preferred in this area, also to reduce the risk of hypogastric plexus injury. The iliac vessels are retracted laterally to expose the L5-S1 disc space. The middle sacral artery and vein, if present, are ligated using clips and/or are cauterized using bipolar cautery.

The L3-4 and the L4-5 disc spaces are most typically approached by rightward mobilization of the great vessels. The lumbar segmental vessels are first ligated. Subsequently, in order to sufficiently expose beyond the midline,

the iliolumbar vein must be isolated and doubly ligated. This will then effectively accommodate mobilization of the great venous structures to the right, so that the right side of the disc can be accessed. The lymphatic channels may be encountered during this dissection, but generally with little clinical consequence. Retractors are placed to maintain the exposure of the disc space, with the vascular structures retracted to the right side. The intended spine procedures can then be performed between L3 and L5. When the retractors are removed, the peritoneal sac is allowed to fall back into anatomic position. The abdominal wall fascia is closed to prevent hernia. The posterior rectus sheath can be left unrepaired. The subcutaneous tissue and the skin are closed in layers.

Midline Incision Retroperitoneal Approach from the Right Side²⁹

The patient's position and preparation are as described above. Fluoroscopy is used to plan the skin incision. The skin incision is typically performed vertically, centered on the operative disc. The skin incision can also be performed horizontally, when only the L5-S1 disc needs to be exposed. The abdominal wall incision is then made vertically on the linea alba. The exposure then follows the medial edge of the right rectus abdominis muscle. This muscle is dissected upward and away from its posterior sheath, and below the arcuate ligament from the peritoneum. Blunt dissection is then performed laterally, pushing the peritoneum posteriorly. The peritoneum is then separated from the inner abdominal wall, working downward and underneath the posterior rectus sheath. This sheath can be incised vertically, from the arcuate ligament, depending on the level to be reached and on the patient's anatomy. The retroperitoneal space can then be accessed, and the peritoneal contents can be retracted superiorly, from right to left. To access the L5-S1 disc space, dissection is performed below the aortic bifurcation. Blunt dissection can be performed with a peanut sponge. Gentle sweeping of the soft tissue is performed from right to left. This tissue may contain the superior hypogastric plexus, and should be treated with care. The sacral vessels are then transected between clips.

To access L4-L5 and levels above, disc exposure will be centered between the medial edge of the right psoas muscle and the lateral edge of the vena cava. The right iliolumbar vein and the segmental vein above the disc are identified, ligated, and transected. In most cases, the

segmental artery may be preserved. The vena cava can then be gently retracted from right to left, providing adequate visualization of the disc and vertebral bodies involved. We have noticed that the majority of patients have a perforating vein, arising from the anterior aspect of L3 and L4 vertebral body, to join posterior to the vena cava. This vein should be coagulated and transected to allow retraction of the vena cava. These collateral venous branches have never been described previously. Once the vena cava can be retracted laterally, the spine will be adequately exposed to accommodate discectomy and implant. The closure follows with the surgical techniques described above.

Transperitoneal Approach to the Anterior Lumbar Spine

The transperitoneal approach can provide excellent bilateral exposure of the L5-S1 region.²⁵⁻²⁸ It also can be used for exposure of L4-5, but this is less favorable because of the typical location of the aortic bifurcation at that vertebral segment. The location of the aortic bifurcation can be determined preoperatively on cross sectional imaging. Mobilizing the great vessels to the right, after ligation of both the segmental lumbar vessels and the ascending lumbar vein, can provide exposure of the L3-L4 segment. The transperitoneal approach is contraindicated, however, in the presence of spinal infection.

A bowel preparation is employed the day before surgery, and broad-spectrum antibiotics are used preoperatively. The patient is positioned supine, with the pelvis elevated. This extended position allows the abdominal contents to shift into the upper abdomen. Fluoroscopy is used to identify the operative spinal segment (typically L5-S1) and to plan the incision. A midline or transverse incision may be used. Of note, the skin incision should be caudal to the umbilicus when exposing L5-S1. A small incision (<6 cm) can typically be used. The incision is performed in the midline and the approach follows through the subcutaneous tissues, fascia, and peritoneum. After the abdominal contents are retracted rostrally, the exposure is maintained with a table-mounted, self-retaining retractor such that the posterior peritoneum is exposed. The pelvic portion of the colon and its mesentery are retracted to the left, and the ureters are identified and protected. The posterior peritoneum is incised in the midline. The peritoneal opening is then extended caudally past the aortic bifurcation by following the course of the right common iliac artery to its bifurcation at the external and internal iliac arteries. This

provides access to the retroperitoneal space. Care should be taken to identify and protect the right ureter where it crosses the right external iliac artery.

The L5 vertebral body, L5-S1 disc space, and sacral promontory are easily palpated and can be well visualized below the aortic bifurcation. The prevertebral tissues, including the hypogastric plexus and the middle sacral artery, are identified and mobilized laterally. Retrograde ejaculation can result from injury to the hypogastric plexus; monopolar cautery should be avoided to reduce this risk. When a large left common iliac vein hinders access to the body of L5 and the sacral promontory, it must be mobilized and protected before proceeding to the discectomy. It is important to note that the left iliac vein occasionally can appear as a flat, white, bloodless ribbon across the L5-S1 disc space. Once well exposed, retractors are placed to maintain the access to the L5-S1 disc space.

The transperitoneal approach can be used to expose proximal to L5-S1, but significant vascular dissection and mobilization is required. For this reason, the retroperitoneal approach is a more appropriate choice for accessing more proximal levels of the spine.

At the conclusion of the spinal procedure, the posterior peritoneum is closed with 3-0 polyglactin 910 (Vicryl) suture, the bowel and omentum are returned to their normal anatomic position, and the abdominal fascia and anterior peritoneum are closed with interrupted sutures. The subcutaneous tissue and skin are closed. Postoperatively an ileus should be expected.

Minimally Invasive Approaches

Laparoscopic and Endoscopic Approaches to the Anterior Lumbar Spine

Laparoscopic and endoscopic techniques require additional equipment and special operating room setup and are associated with a steep learning curve.^{26,27,30-36} Laparoscopic ALIF can be used as a stand-alone procedure, or it can be combined with posterior instrumented fusion using either minimally invasive or open techniques.

Laparoscopic or Endoscopic Retroperitoneal Approaches

The endoscopic retroperitoneal approach was developed for urological surgery. McAfee and colleagues adapted it to be used for lumbar spine fusion. The procedure can be performed using CO₂ insufflation, balloon insufflation (gasless), or a combination of both techniques.

The patient is typically placed in the lateral decubitus position, but LeHuec has also described the approach performed in the supine position. A 2- to 3-cm transverse skin incision is created, centered on a line between the 11th rib and the anterior superior iliac spine. Blunt dissection is carried down through the abdominal muscle layers using an endoscopic trocar until the fatty retroperitoneal space is reached. Once the retroperitoneal space has been manually confirmed, the dissection balloon placed and then inflated creates a retroperitoneal cavity. At this point the balloon is removed and a self-retaining retractor system or CO₂ insufflation is used to maintain the retroperitoneal cavity. A minimum of three ports is placed; these are for retractors, endoscope, and working instruments. Once the appropriate level has been confirmed fluoroscopically, the psoas muscle is elevated from the spine. The discectomy and fusion are then performed.

Laparoscopic and Endoscopic Transperitoneal Approach

The laparoscopic transperitoneal approach can also be used to gain access to the lower lumbar spine. Special attention to the preoperative setup is necessary to increase the efficiency of the surgeon using this approach. The C-arm monitor and the video monitor are positioned to allow the surgeon an optimum view of both. The patient is placed supine on a radiolucent table. The pelvis is elevated to accentuate lordosis at the lumbosacral junction and the knees are flexed. Straps are placed on the patient's ankles to prevent sliding; a steep Trendelenburg position is required during the procedure to displace the abdominal viscera rostrally out of the pelvis. A nasogastric tube and Foley catheter are placed to decompress the stomach and bladder, respectively.

A small incision is made above the umbilicus. A Veress needle is carefully placed into the peritoneal cavity, which is insufflated with CO₂ to 10–15 mm Hg. This allows for insertion of a 10-mm portal through the same incision. A laparoscope is inserted through the trochar and the contents of the cavity are inspected. The endoscope can be manually controlled or in some cases manipulated by a voice-controlled robotic arm (AESOP 2000, Computer Motion, Goleta, CA). Using a 30°-angled laparoscope, two 5-mm secondary portals are placed under direct endoscopic visualization through the patient's right abdominal wall. A single 5-mm portal is placed in the left abdominal wall through which a fan retractor is placed. The sigmoid

colon is retracted to the patient's left using a suture attached to a Keith needle, which is passed through the abdominal wall, looped through the sigmoid mesentery, and passed back through the abdominal wall adjacent to the first puncture. The suture is then tied externally. The posterior peritoneum is divided at the base of the sigmoid colon using sharp dissection. The middle sacral artery and vein are identified, isolated, and transected. The presacral autonomic plexus is swept laterally using blunt dissection. Use of unipolar cauterization should be avoided in this area since it has been associated with autonomic plexus nerve injury and RE. The disc space of interest is identified fluoroscopically and laparoscopically. After a generous exposure of the anterior spinal column, a suprapubic incision is made and a special trochar is placed through the abdominal wall. The position of the suprapubic incision and portal is determined using the fluoroscopic C-arm in the lateral position. The plane of the disc space in the anteroposterior dimension is projected to the suprapubic region.

Mini-Open Retroperitoneal Approaches^{12,34,37}

Lateral Mini-Open Approach to L2 Through L5

This left-sided approach is performed with the patient in a lateral position. The operating table is rotated 20°–40° toward the surgeon, who is standing at the back of the patient. Lateral fluoroscopy is used to project the disc space onto the skin, and the AP fluoroscopy is used to mark the center of the disc space as well. The approach is started with a 4-cm skin incision centered above this projection in an oblique direction. The muscle fibers of the lateral abdominal wall (external oblique, internal oblique, and transversalis) are bluntly separated to expose the retroperitoneal space. The retroperitoneal space should be entered through the transverse abdominal muscle far lateral to avoid penetration of the peritoneum, which is typically less adherent to the lateral aspect of the abdominal wall. Blunt dissection is performed with cottonoids and modified Langenbeck hooks to expose the psoas muscle. The spine is then inspected, following the anteromedial "slope" of the psoas muscle. The genitofemoral nerve, which passes along this part of the psoas muscle, must be preserved. The anterolateral attachments of the psoas muscle are sharply dissected from the lateral circumference of the disc space, thus exposing the anterolateral aspect of the anterior longitudinal ligament.

The disc space is then confirmed by fluoroscopy, and blunt dissection is used to expose 5–10 mm of the adjacent vertebral bodies. At L4–L5, the left common iliac vein may obstruct the anterior medial angle of the surgical field and should be mobilized bluntly.

A frame-type retractor, with independently adjustable blades, maintains the surgical exposure. Two anchoring screws are inserted through drill holes in the adjacent vertebral bodies and serve as an anchor for the retractor. The anterolateral circumference of the segment to be fused is now exposed, which offers various options for anterior interbody fusion. For example, we perform 270° fusion, including posterior instrumentation, in most of our patients. In this setting, we prefer to use autologous iliac bone graft, which can be harvested through the same skin incision, and before introduction of the retractor. Other types of anterior interbody fusions are possible, however, including the use of homografts or allografts. The graft is mounted to a graftholder and impacted in “press-fit” fashion into the intervertebral space. Additional cancellous bone, harvested from the iliac crest as well as from the vertebral bodies, is impacted into the intervertebral space.

Midline Microsurgical Approach to L5-S1

Either the transperitoneal or the retroperitoneal approach can be used to expose the lumbosacral junction through this midline approach. In either case, the patient is positioned supine. Trendelenburg position is applied with the pelvis elevated, the lumbar spine hyperextended, and both hips abducted.

Lateral fluoroscopy is used to mark the orientation of the L5–S1 disc, to plan the skin incision. A “corridor line” is drawn onto the abdomen, and a 4-cm skin incision (longitudinal or transverse) is performed on (or centered on) the midline of the abdomen, overlying the planned corridor to L5–S1. The operation can be performed with a surgical microscope, or with headlamp and loupes. The surgeon stands between the legs of the patient.

The peritoneum is exposed by sharp dissection of the rectus sheath (linea alba) in the midline. In slim patients, the anterior circumference of L5–S1 can be exposed by blunt retroperitoneal dissection along the abdominal wall on the right side, crossing the common iliac artery and vein as well as the ureter. The prevertebral soft tissue, including the fibers of the superior hypogastric plexus, is gently pushed from the right to the left side. Thus, the major branches of the plexus can be preserved. Similar to other anterior

lumbar approaches, monopolar cautery should be avoided and the use of bipolar coagulation should be restricted to a minimum. The median sacral vessels are exposed, clipped, and dissected. In obese patients, the transperitoneal route may be preferred. In this instance, the peritoneum is exposed, split in the midline, and armed with sutures. The mesentery with the ileum is carefully pushed into the upper left abdominal cavity with sponges. The sigmoid colon is carefully retracted to the left. A soft tissue retractor such as the Miaspas mini ALIF retractor (Aesculap GmbH & Co., Tuttlingen, Germany) is placed such that the promontory is well visualized. The parietal peritoneum is incised with micro scissors in a craniocaudal direction. The semicircular incision is started approximately 5 mm medial to the right common iliac artery. The retroperitoneal fat tissue with the superior hypogastric plexus is exposed, bluntly dissected, and carefully retracted to the left side as described above. The middle sacral artery and vein, if present, can be ligated using clips or cauterized using bipolar cautery. The retractor can then be inserted under the parietal peritoneum, exposing the anterior aspect of the vertebral column.

Anterior Interbody Fusion Techniques

Disc Space Preparation

The anterior longitudinal ligament can be divided in an H-shape, and then bluntly dissected from the anterior aspect of the annulus fibrosus. The annulus fibrosus is then incised so that the interbody material can be removed. The endplates are prepared with curettes, taking care to maintain the structural integrity of the vertebrae. It is important that the discectomy be completed back to the posterior longitudinal ligament. Release of the posterior annulus is helpful so that balanced interbody distraction occurs throughout the disc space and not just anteriorly. This is particularly relevant in cases of significant disc space collapse. Herniated disc material may be retrieved through posterior annular defects. To assist with interbody access, interbody space distracters can be impacted unilaterally. After complete discectomy, resection of endplate cartilage, exposure of bleeding subchondral bone, and posterior release, the disc space may be ready for implant insertion.

Implant Insertion and Instrumentation

Implant selection and application is specific to the clinical scenario, and to the implant being used. In any case,

radiographic confirmation should be considered to ensure appropriate placement of the implant(s). The reconstruction of the interbody space should be performed to achieve anatomic restoration of interbody height and alignment in both the coronal and sagittal planes, when possible. While restoration of the foramen volume and alignment can be helpful in providing indirect neurological decompression, care to not “overstuff” the interbody space (or create a super-anatomic height restoration) may reduce the risk of adverse postoperative neurological symptoms. In the case of posterior element deficiency, such as pars lysis or posterior element fracture, the stability of an anatomically sized interbody device may be augmented by anterior instrumentation, to avoid “overstuffing” the interbody space.

■ INDICATIONS FOR ANTERIOR LUMBAR INTERBODY FUSION

As compared with the posterior interbody fusion procedures, ALIF provides direct access to the anterior elements of lumbar spine, allowing for complete disc excision and lumbar column manipulation. Because the vertebral body provides 90% of the articular surface area of the lumbar segment and supports 80% of the spinal load,³⁸ ALIF offers considerably larger bone surface area in a biomechanically compressive environment appropriate for fusion. It also offers an opportunity to reduce segmental deformity with annular releases, thereby relying on apophyseal bone for reconstruction. These reasons are among those used to explain why ALIF may offer improved fusion rates, as compared to posterior element fusion alone. Other theoretical advantages of ALIF over posterior fusion include direct removal of the interbody pathology, disc height restoration, less risk to the nerve roots and dura, and restoration of segmental coronal and sagittal alignment. With these proposed advantages, ALIF is helpful in cases of segmental instability such as posterior element deficiency, particularly at the lumbosacral junction, for treatment of deformities, unstable fractures, infections, and tumors or other infiltrative lesions causing significant segmental instability.

Treatment of Trauma with ALIF

Anterior lumbar interbody fusion was applied to lumbar trauma in an early stage of its development,³⁹ but did not gain significant popularity until the emergence of anterior instrumentation and other implants that could reliably provide circumferential reconstruction. From the anterior approach, vertebral corpectomy or discectomy, followed by direct decompression of the spinal canal can be achieved.

Subsequent restoration of anterior column stability can also be achieved, including with reestablishment of the normal sagittal and coronal alignment.^{40,41} Anterior structural support can be provided by allograft, autograft, or prefabricated implants. Some authors⁴² regard significant reconstructive anterior instrumentation to be technically challenging because of the major vessels and their relationship to the potentially bulky instrumentation. An alternative choice is to achieve decompression and interbody reconstruction from an anterior approach, followed by posterior instrumentation and fusion.

Treatment of Infection with ALIF

The anterior approach can be well suited to treat various infectious pathologies of the lumbar vertebral body and disc. Discitis and osteomyelitis compromise the stability of the anterior and middle columns. Structural consequences include deformity and functional instability. Back pain and neurological sequelae can also develop from epidural abscess. Common infectious causes of osteomyelitis include gram-positive bacteria (especially *Staphylococcus aureus*), and, less often, tuberculosis. Roughly half of all spinal osteomyelitis infections occur in the lumbar region.

Surgical intervention is indicated when there may be significant deformity, neurological deficit, and in cases that are refractory to medical management. The anterior approaches can provide access to the infected focus and, as such, is very effective for debriding the infected tissue. Furthermore, the anterior approach is well suited to reconstruction of the tissue defect. For these reasons, it has been adopted by many surgeons.^{27,43-45} Several reports have suggested that posterior stabilization should follow an anterior aggressive debridement and anterior reconstruction of the lumbar segment(s).^{44,46}

Treatment of Degenerative Disease with ALIF

The most common use of ALIF may be in the treatment of degenerative lumbar disorders. These include a variety of problems, such as discogenic back pain, degenerative deformity such as scoliosis and spondylolisthesis, herniated discs, and other degenerative deformities.⁴⁷ Anterior lumbar interbody fusion was first used in the treatment of degenerative disease in 1948.⁵ Since that time, several studies have reported ALIF to be safe and effective in relieving degenerative radicular and back pain.⁴⁸⁻⁵¹ Some surgeons have suggested that stand-alone ALIF is a viable

option for the treatment of patients with one- or two-level painful disc disease.^{50,51} It is widely recognized, however, that spinal fusion performed for the treatment of degenerative lower back pain is plagued by a poor predictability of pain relief. For treatment of a degenerative deformity, standalone ALIF may not be adequate, and correction of rigid curves typically requiring a combined anterior and posterior approach may be indicated.^{51,52} In the treatment of such deformities, particularly at the lumbosacral junction, the use of structural interbody grafting may improve the fusion rate, improve stability and sagittal balance, decreases strain in posterior instrumentation, and prevent implant failure.⁵²⁻⁵⁶ Several studies have reported that adult patients with spinal deformities can significantly achieve promising clinical outcomes when ALIF was used in conjunction with posterior instrumented fusion.⁵⁷⁻⁶⁰

Treatment of Isthmic Spondylolisthesis with ALIF

Traditionally, isthmic spondylolisthesis cases are categorized according to the severity of the displacement, as either low-grade (grade I and II) or high-grade (grade III and IV). Patients with low-grade isthmic spondylolisthesis often can be adequately treated nonoperatively. Surgery is indicated, however, if symptoms are disabling or in cases of significant or progressive neurologic symptoms. Fusion is a typical component of the surgical treatment for either low-grade or high-grade spondylolisthesis. Many surgeons have recommended ALIF for isthmic spondylolisthesis, particularly at L5-S1, with its ability to increase the intervertebral height and provide indirect decompression of the foramen, permanently while preserving or improving the segmental lordosis.⁶¹⁻⁶³ Clinical studies also have verified the effectiveness of ALIF in stabilizing the listhesis and alleviating the associated symptoms.^{51,63-67} ALIF has frequently been used in combination with posterior instrumented fusion, especially in the treatment of high-grade isthmic spondylolisthesis, which may help achieve the most reliable fusion and a successful clinical outcome.^{51,63-70}

Treatment of Iatrogenic Problems with ALIF

Iatrogenic lumbar pathologies that may be amenable to treatment with ALIF include instability or deformity related to prior surgery, adjacent segment disease with instability, construct failure, and pseudarthrosis.

While recurrent disc herniation may not be universally regarded as an iatrogenic problem, it has been treated with

ALIF. Vishteh and Dickman⁷¹ reported on anterior lumbar microdiscectomy and interbody fusion for the treatment of recurrent disc herniation in 2001. Choi et al.⁷² found ALIF to be an effective procedure with satisfactory clinical results in selected patients with a recurrent lumbar disc herniation.

Failed back surgery syndrome (FBSS) is a term that has been used to describe patients who have pain unresolved by prior surgical intervention. Coventry and Stauffer^{73,74} first described the use of anterior interbody fusion for treatment of FBSS. They reported good results for patients who underwent ALIF for treatment of FBSS. Subsequent surgeons also reported satisfactory reduction in back pain following ALIF performed at levels of previous posterolateral fusions⁷⁵⁻⁷⁷ Fujimaki and colleagues⁷⁸ reported a 97% fusion rate in 38 salvage cases treated with ALIF without instrumentation. In 1997, Kostuik⁷⁹ described 51 patients who had undergone revision anterior instrumented interbody fusion. The clinical success rate approached 70%, and the reported incidence of subsequent pseudarthrosis was 9%. Kuslich and colleagues⁸⁰ similarly reported a 96% fusion rate and a 70% clinical success rate in a group of 76 patients who underwent anterior fusion with stand-alone Bagby-Kuslich cages, after prior decompression. Results of Duggal et al.⁸¹ resonated with these previously published series, demonstrating statistically significant improvements in back pain, leg pain, and functional status. Albert and colleagues⁸² reported in 2000 on 37 consecutive patients with symptomatic lumbar pseudarthrosis who underwent combined APLFs. Significantly improved radiographic and functional results were reported in this case series.

Flat-back syndrome typically is an iatrogenic problem, characterized by forward sagittal imbalance, and frequently observed in patients who underwent posterior scoliosis fusion with early distraction-type instrumentation. It also can occur, however, with modern fusion techniques.⁸³ The surgical treatments of these complex imbalances can be challenging. LaGrone et al.⁸⁴ showed that anterior fusion results in a higher fusion rate and a lower amount of sagittal plane imbalance. Circumferential fusions frequently are reasonable choice.⁵¹

Treatment of Segmental Deformity with ALIF

Anterior lumbar interbody fusion can be applied to other spinal deformity conditions. Anterior instrumented fusion

has been used for many years in the treatment of adolescent idiopathic scoliosis (AIS). The anterior approach can facilitate deformity correction including derotation, can help maintain lumbar lordosis, reduce the number of fused segments, and can reduce operative blood loss.⁸⁵⁻⁹¹ Anterior lumbar interbody fusion can also be a helpful reconstruction and fusion adjunct to posterior deformity surgery, particularly when a long fusion to the sacrum is performed. The additional use of dual rod systems with interbody cage and graft has been associated with a relative decrease in instrumentation failures, loss of correction, and pseudarthrosis.⁹²⁻⁹⁴ Recent evidence also suggests that the anterior approach in the treatment of thoracolumbar and lumbar curves in AIS offers good long-term clinical outcomes.⁹⁵

■ CONTROVERSIES RELATED TO ANTERIOR LUMBAR INTERBODY FUSION

Stand-alone Anterior versus Combined Anterior/Posterior Instrumentation

One attractive attribute of ALIF is the potential to achieve interbody fusion without requiring posterior muscle dissection or exposure of the neural elements. The early attempts at using this anterior only strategy were met with certain shortcomings, however. The early clinical results using anterior interbody autograft or allograft (alone) were poor.⁸ Dennis et al.⁹⁶ reported their experience in treating 31 consecutive patients with ALIF using both iliac allograft and autograft bone in the interbody space. They reported that 100% of their patients demonstrated postoperative disc space height loss, to at least the preoperative height. A significant fraction of their patients (46%) developed postoperative interbody height less than their preoperative height. Watkins⁹⁷ also noted that autogenic iliac crest tricortical grafts typically exhibited partial resorption, which was associated with loss of interbody height, as well as subsidence, before healing. The recognition of these shortcomings motivated the development of interbody cages and other implants.

The stability of a stand-alone interbody device depends primarily on the compressive forces produced by tension engendered in the remaining annulus fibrosus. The magnitude of this compressive force reduces by 25%; however, 15 minutes after the initial device insertion, due to relaxation of the annular fibers.⁹⁸ This observation helps

to explain why stand-alone ALIF procedures have been seen to exhibit a wide variety of fusion rates, and to exhibit potential for subsidence and migration.^{99,100}

The design of the interbody device greatly affects biomechanical stability. Andreou and colleagues¹⁰¹ compared the initial segmental stability of five stand-alone ALIF interbody devices (I/F, BAK, TIS, SynCage, and ScrewCage) in a human cadaveric study. They reported a reduction in the range of motion (ROM) and an increase the neutral zone (NZ) in all loading directions. The BAK and TIS cages demonstrated the largest NZ increase in flexion/extension and lateral bending. The degree of geometrical cage-end plate surface mismatch was responsible for the differences in NZ between cages. Cages with sharp teeth were found to exhibit greater pullout forces. Both the height and the sagittal profile of the devices influenced the initial stability. The residual ROM was found to be related to the degree of micro-motion at the cage-end plate interface. Various types of internal fixation, such as anterior plates,¹⁰³⁻¹⁰⁶ pedicle screws^{102,104-108} and translaminar screws,^{103,107,109} can augment the stability of stand-alone ALIF by decreasing the ROM and increasing the stiffness of the segment. Kim et al.¹¹⁰ performed a finite element analysis investigating motion and stress at the bone-implant interface in a model of ALIF augmented with pedicle screw fixation (PSF). They reported that the addition of PSF to the stand-alone ALIF was associated with greater segmental stiffness, reduced relative motion, reduced bone deformation, and reduced bone stress at the cage-bone interface. They concluded that geometric constraints imparted by PSF substantially reduced the stress and the motion, and may contribute to improved bone ingrowth at the bone-cage interface, compared with the stand-alone ALIF.

Stand-alone ALIF with interbody allograft or autograft may be associated with subsidence of the interbody graft and loss of segmental lordosis. With the advent of cages, many investigators reported a relative decrease in the degree of subsidence, and better maintenance of segmental lordosis. Choi et al.¹¹¹ reported the results of using paired stand-alone rectangular cages; despite a reduction in disc height compared to that seen with the initial intraoperative distraction, the disc height at the final recent follow-up was significantly greater than that measured preoperatively. Hsieh et al.¹¹² examined pre- and postoperative interbody height and alignment in patients who underwent either ALIF or transforaminal lumbar interbody fusion (TLIF). For the ALIF group, they reported an increase in segmental lordosis from 7.1° to 15.4°, and an increase of

65% in disc height after surgery. McAfee et al.¹¹³ also measured the interbody height before and after L4/L5 ALIF using Bagby and Kuslich cages. While they reported an initial subsidence (12% loss of interbody height between the intraoperative and the 24 months radiograph), they also reported an overall increase of approximately 60% between the preoperative and final (24 months) measurement. Pavlov et al.¹¹⁴ reported radiologic results in 42 patients who had undergone one or two-level ALIF with SynCage and supplemental posterior fixation with trans-laminar or pedicle screws. Average intervertebral height was improved from 8.7 mm to 17.6 mm. The average lordosis was also increased (10.6° for the fused segment).

Anterior lumbar interbody fusion appears to offer excellent improvement in interbody height and alignment. The study by Niemeyer et al.¹¹⁵ supported this, and furthermore reported that ALIF may offer better interbody reconstruction than TLIF. This study compared ROM and NZ following interbody reconstruction by either ALIF or TLIF. In both the stand-alone scenario, and following supplemental posterior PSE, ALIF provided better segmental stability than TLIF cage in flexion-extension and in axial rotation.

The fusion rate for stand-alone ALIF varies considerably from one study to another. Most authors agree, however, that supplemental fixation with ALIF provides a better biomechanical environment, and may result in an improved fusion rate. Naffis et al. reported the fusion rates measured by thin-section CT in four ALIF cohorts: 25 cases with stand-alone ALIF (51% fused); 15 ALIF with trans-laminar screws (58% fused); 17 ALIF + unilateral pedicle screws (89% fused, $P < 0.01$) and 24 ALIF + bilateral pedicle screws (88% fused, $P < 0.01$).

The reported clinical results following ALIF have also been variable. Furthermore, several ALIF clinical studies have shown no correlation between clinical outcomes and fusion rates.^{63,116,117} Recently, Li et al.²³ reported on the safety and efficacy of the anterior Carbon I/F Cage used in 112 patients who underwent single-level ALIF. They concluded that the anterior I/F Cage is a safe surgical option in the treatment of single-level lumbar degenerative disc disease. As a stand-alone construct, the I/F Cage yielded suboptimal radiographic and clinical outcomes, however. The authors suggested that additional benefit might be gained from supplemental posterior stabilization. Strube et al.²⁴ enrolled 80 patients in a prospective cohort study comparing single-level ALIF with APLF. In contradistinction to other studies, they found that stand-alone ALIF was

associated with better clinical results than APLF. There were no differences seen in fusion rate 41 months after surgery. They suggested that if a posterior approach is not needed for decompression or reduction, a stand-alone ALIF might be a favorable strategy.

While successful arthrodesis is one goal following ALIF, successful fusion does not always correlate with a successful clinical result. It currently is unclear whether stand-alone ALIF is sufficient for arthrodesis and what degree of stability is required to guarantee a satisfactory clinical outcome.

Open versus Minimally Invasive ALIF

There is less controversy regarding the relative benefits of open and minimally invasive ALIF. Since the development of the original open ALIF, the technique has been modified several times. Minimally invasive spine surgery is becoming more frequently used, in part due to the reported benefits. These benefits include decreased muscle damage, shorter hospitalization time, and quicker recovery.

Minimally invasive ALIF includes the laparoscopic and mini-open procedures. While there are theoretical advantages of minimizing soft-tissue damage during the ALIF exposure, the number of studies published regarding minimally invasive ALIF is still small. Saraph et al.¹¹⁸ conducted a retrospective study comparing conventional (open) with the mini-open extraperitoneal approach; surgical time and blood loss were reduced with minimally invasive extraperitoneal ALIF. They also reported a significant improvement in postoperative back pain in the minimally invasive group, while all other clinical parameters showed no significant difference. Zdeblick and David³⁴ prospectively compared laparoscopic ALIF with mini-open ALIF; they were not able to find a difference in operative time, blood loss, or length of hospital stay for one-level fusions. The laparoscopic approach, however, had a higher complication rate, and a slightly longer operative time when used for two level cases. Similarly, in a retrospective study, Kaiser et al.¹¹⁹ found no difference in blood loss, but operative times were significantly longer for L5/S1 laparoscopic ALIF procedures (173 minutes compared with 145 minutes), and length of hospital stay was shorter (2.8 days compared with 3.5 days). Importantly, for L5/S1 fusions, they reported a significantly higher rate of RE for laparoscopic ALIF procedures compared with mini-open ALIF (45% compared with 6%). Chung et al.¹²⁰ retrospec-

tively reported that operative time was significantly longer for laparoscopic ALIF procedures (158 minutes compared with 83 minutes), although blood loss and length of hospital stay were not significantly different. In this study, clinical and radiographic outcomes were similar after 2-year follow-up. Based on these reports, in part, the general trend appears to be moving away from laparoscopic/endoscopic procedures, and toward mini-open procedures.

COMPLICATIONS

Anterior lumbar interbody fusion complications can be categorized as either intraoperative or postoperative. The postoperative complications can be sub-divided into the early late events. Complications also can be classified by system, such as visceral, vascular, neurologic, incision and graft related.

Most intraoperative complications are approach-related. Perforation of the peritoneum during a retroperitoneal approach is not uncommon. Urinary bladder, ureter, and gastrointestinal injuries may occur by misplaced retractors or overaggressive retraction. Misplaced hardware may result in neurologic or vascular injury; dural tears and nerve root injury have been reported¹²¹ as well as catastrophic bleeding.¹²²⁻¹²⁵ The superior hypogastric plexus that innervates the internal vesicle sphincter controls the normal ejaculatory reflex; this plexus can be damaged during anterior lumbar exposure, resulting in RE. Use of monopolar electrocoagulation¹²⁶ in the area of the anterior lumbar spine has in particular been implicated in injury to the superior hypogastric plexus. This is discussed in more detail below. Early postoperative complications include ileus, infection, hematoma, deep vein thrombosis, transient and permanent nerve injury, while late complications include hardware failure, bone resorption, adjacent segment disease (ASD) and pseudarthrosis.

Vascular injury can be a serious complication, often associated with considerable morbidity. Previous literature suggested that the most common vascular injuries are tears and lacerations of the aorta, iliac veins, and vena cava, with injury rates ranging widely from 0% to 18.4% in various studies.¹²²⁻¹²⁹ An indirect vascular complication is ischemic injury, such as that caused by partial or complete occlusion of the left iliac artery due to retraction.¹³⁰ Ischemic complications have also developed from the formation of thrombosis within this vessel and its branches, also typically attributed to forceful or prolonged retraction.^{124,131-136}

Dural tear is not an uncommon complication during ALIF; the incidence has been reported to be >10%.^{83,137} The incidence of neurologic complications, however, is difficult to determine owing to differences in how these complications are defined. Kuslich et al.⁸⁰ reported persistent neurologic symptoms in 2.0% of ALIF cases using BAK cages, while Scaduto et al.¹²³ reported 1% rate of neurologic injury using a threaded cylindrical cage.

The reported incidence of RE after ALIF varies widely in the literature.¹³⁸ A large worldwide survey of surgeons published in 1984 reported that the incidence of RE was rare (0.42%).¹³⁹ Other studies reported higher incidences, particularly those studies evaluating the laparoscopic transperitoneal approaches.^{33,140-143} While Tiusanen et al.¹⁴⁴ indicated that RE occurred only after a transperitoneal procedure, Flynn and Price¹³⁹ concluded that the approach (transperitoneal vs. retroperitoneal) was not related to the risk of RE. In one prospective study, Sasso et al.¹⁴⁰ reported the transperitoneal approach to be associated with a 10-fold greater risk of postoperative RE than the retroperitoneal approach. Carragee and colleagues¹⁴⁵ retrospectively compared the incidence of RE in patients who had previously undergone ALIF with and without rhBMP-2 (Infuse). Their retrospective chart review revealed that 5 of the 69 (7.2%) patients treated with rhBMP-2 experienced postoperative RE compared with 1 of the 174 patients (0.6%) treated with autograft. In another retrospective cohort study, Lindley and colleagues¹⁴⁶ reviewed 95 patients who underwent L5/S1 retroperitoneal ALIF. They reported that 4 of the 54 (7.4%) rhBMP-2 patients experienced postoperative RE. They also found, however, that 4 of the 41 (9.8%) patients treated with anterior disc replacement (ADR) [and without bone morphogenetic protein (BMP)] by the same surgical approach had postoperative RE. They suggested that retroperitoneal approach rather than the use of BMP seems to be responsible for this risk.

In comparison to the traditional open approach ALIF, laparoscopic/endoscopic or mini-open ALIF may be associated with a significantly higher rate of complications. Escobar et al.¹⁴⁷ reported an 18% incidence of neural injury and 25% incidence of RE. Twenty-five (11%) of these cases had to be converted to open procedures because of intraoperative complications. Regan et al.³³ reported a 19.1% complication rate for laparoscopic procedures as compared to 14.1% for open ALIF procedures. Zdeblick and David³⁴ also reported significantly higher complication rates in patients undergoing laparoscopic ALIF (20%) as compared to open (4%) at the L5/S1 level.

Adjacent segment disease is one potential late complication related to ALIF. There are limited investigating ASD following ALIF, but a few conclusions can be derived from studies with longer term follow up. In a retrospective study, Min and colleagues¹⁴⁸ compared patients that developed ASD to patients who did not develop ASD following anterior or posterior instrumented lumbar fusion at L4-L5. He reported that the proportion of patients who underwent ALIF in the non-ASD group was 77.8% as compared to 36.7% in the ASD group. This suggests that ALIF (alone) may reduce the incidence of ASD by avoiding damage to posterior structures. Posterior surgical approach is known to be one risk factor for ASD.¹⁴⁹ The ability to restore lordosis, to restore interbody height, and to correct spinal misalignment are other ALIF attributes that may offer a protective effect on the long-term adjacent level stresses.¹⁵⁰⁻¹⁵²

■ APPLICATIONS OF ANTERIOR LUMBAR INTERBODY FUSION IN REVISION SURGERY

Revision anterior lumbar surgery can present a significant challenge for the access surgeon in particular. Revision exposure of the spine requires mobilization of the peritoneal sac, which may be adherent to the anterior abdominal wall muscles. Revision exposure also requires mobilization of the major vessels and ureter, which may be encased in fibrous tissue and, thus, adherent to each other and to the anterior surface of the spine. This can present an insurmountable problem depending on the type of revision anticipated. Nguyen and colleagues¹⁵³ reported an 89% incidence of vascular complications with revisions at L4-L5 and a 40% incidence of vascular complications with revision exposure at L5-S1. Schwender and colleagues¹⁵⁴ reported that complications associated with revision anterior lumbar surgery were 3-5 times more frequent than for primary lumbar exposures in his series, specifically for venous injuries and RE.

■ INNOVATIONS RELATED TO ANTERIOR LUMBAR INTERBODY FUSION

Some early experience with robot-assisted anterior lumbar surgery has recently been published. Both Beutler¹⁵⁵ and Yang¹⁵⁶ independently performed a robotic-assisted ALIF in a porcine model, using the da Vinci Surgical System. Beutler reported that the anterior transperitoneal approach

to the lumbar spine was accomplished with enhanced visualization and dissection capability with maintenance of pneumoperitoneum using the robot. Blood loss was minimal. The visualization of the interbody space and surrounding structures was described as equivalent to or better than traditional open or other laparoscopic techniques. Yang reported that while the entirety of this first trial procedure took 6 hours, the use of the da Vinci System for ALIF was felt to be safe and effective. The use of this advanced technology may be beneficial, particularly if it can indeed reduce the risk of approach-related complications. With this goal, future development of robotic techniques for anterior lumbar spine applications is anticipated.

■ KEY POINTS

- ALIF is advantageous because of the possibility to easily and thoroughly resect the pathological disc while sparing the posterior structures.
- Stand-alone ALIF with well-designed Cage or augmentation of ALIF with anterior or posterior fixation will increase the segmental stiffness, which is supposed to promote fusion rate.
- Minimally invasive ALIF has the theoretical advantages over the common open ALIF, but it may be accompanied with long and steep learning curve and even higher rates of complications.

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Posterior Lumbar Interbody Fusion

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Snapshot

- » Modifications to the Original Surgical Technique
- » Patient Selection
- » Operative Technique
- » Complications
- » Minimally Invasive Approaches

INTRODUCTION

First introduced in the 1940s, posterior lumbar interbody fusion (PLIF) is a common surgical technique for treating pain and/or instability of the lumbar spine. In 1943, Cloward devised a procedure for treating ruptured lumbar intervertebral discs that restored the intervertebral space while immobilizing the adjacent vertebral bodies, initially using impacted blocks of iliac crest bone then switching to cadaver bone in 1947.¹ This procedure, known as PLIF, became popular for spinal stabilization in the early 1950s after Cloward's reports of "complete long-term cures" in over 85% of patients—a "cure rate" that was 30–50% higher than that reported after simple disc removal.¹ The use of PLIF remained limited, however, due to significant technical demands and a high complication rate, including pseudarthrosis and nerve root irritation.^{2,3}

Posterior lumbar interbody fusion provides several theoretical advantages over the traditional dorsal or intertransverse (posterolateral) fusion techniques. Posterior lumbar interbody fusion enables access to the posterolateral and intervertebral disc space from a single posterior-only approach and provides increased graft load sharing because the center of fusion is proximate to the center of motion.⁴ In addition, PLIF creates a wider surface area of bone-to-graft contact⁵ and provides a rich cancellous blood supply to the graft, both of which increase the likelihood of solid fusion.⁶

The goals of PLIF are to restore and maintain intervertebral disc space height, provide sagittal and coronal correction while indirectly decompressing the nerve roots, arrest micromotion and hypertrophic degenerative disc disease (DDD), restore load-bearing capacity to anterior structures, achieve solid fusion, remove the disc that may be a source of back pain, and prevent recurrent disc herniation.^{2,3,5–10} Posterior lumbar interbody fusion is theoretically an ideal technique for the treatment of lumbar spine instability, whether congenital, acquired, or iatrogenic, because lumbar interbody fusion eliminates the instability that is a primary cause of pain. The success rate of PLIF is high, with arthrodesis rates between 77% and 100%.^{3,11–17}

MODIFICATIONS TO THE ORIGINAL SURGICAL TECHNIQUE

Over the past six decades, there have been many modifications to the original PLIF technique, with the goal of maximizing surgical ease and safety and minimizing morbidity. Although the basic surgical principle has remained the same,¹⁸ improved posterior interbody access and implant designs have resulted in shorter operating times, less neurologic injury, and improved outcomes.¹⁸ Posterior instrumentation was devised to increase fusion rates. Pedicle screw instrumentation in the 1970s allowed wider resection and wider decompression; spinal stabilization was achieved using pedicle screw-rod and pedicle screw-plate constructs.¹⁹

In 1977, Lin described a technical modification to the original PLIF technique, which involved preservation of the posterior portion of the motion segment, total discectomy to provide a larger area of bony contact between the grafts, only partial decortication of the endplates, and a functional and mechanical “unigraft” concept. Lin reported a 94% fusion rate and improved postoperative stability.^{20,21} Blume²² reported that unilateral PLIF with a bone dowel and cancellous bone chip preserved the posterior ligament structure. Branch’s modified PLIF, described in 1987, precluded the need for either banked bone or harvested iliac crest bone and, despite the removal of the posterior elements, provided posterior stability with the facet fusion.²³ Steffee and Sitkowski introduced the use of pedicle screws and plate fixation to supplement interbody fusion,²⁴ resulting in improved spinal stability,¹⁸ an increased rate of arthrodesis, and a reduced rate of graft migration.² Titanium interbody cages became prevalent in the 1980s, resolving the problems arising from autograft harvesting² and providing containment for the interbody graft. The titanium cages provided immediate spinal stability, restoration of the disc space, and an increased surface area, all of which contributed to successful fusion.²

Another modification to the original PLIF technique involved removing almost the entire facet complex. Unilateral or bilateral facetectomies became increasingly popular because they allowed the disc space to be approached in a manner limiting thecal sac and nerve root retraction, thus minimizing nerve root injury. Abumi et al. found that a unilateral facetectomy produced fewer increases in flexion and axial rotation.²⁵ Zhao et al. found that a unilateral facetectomy and hemilaminectomy enabled sufficient decompression for the placement of a single threaded interbody fusion cage while maintaining posterior supporting spinal structures.^{18,26,27} Shin et al. performed PLIF with two cages via a unilateral medial facetectomy and hemilaminectomy, which enabled sufficient decompression and solid interbody fusion while preserving most of the posterior elements.²⁸ When there is limited disc space, nerve root anomalies blocking access to the disc space, or epidural scarring, PLIF may be performed with a unilateral cage.^{5,7} Although bilateral cage PLIF is used routinely, it has a greater cost, may destroy many of the lumbar posterior elements, and may cause bilateral nerve root damage.^{5,27} Unilateral cage PLIF is less expensive because of fewer transfusion requirements, less operating time, and less blood loss,⁵ and has a lower risk of both epidural fibrosis and injury to neural structures from excessive root retraction.²⁹ For both

unilateral and bilateral cage PLIF, fixation stability, and both radiological and clinical results, were similar.⁵

Interest in PLIF was renewed in the 1990s after new interbody implants, improved graft sources, and improved instrumentation led to increased fusion rates.^{3,30-32} In 1997, Ray reported an average fusion rate of 96% using threaded cages.³³ Several years later, Chitnavis et al. and Brantigan et al. reported 95% and 98.9% fusion rates, respectively, using carbon fiber cages.^{34,35} Posterior lumbar interbody fusion has now become a widely accepted and reliable treatment option for patients with DDD, degenerative spondylolisthesis, and spinal deformity.²

PATIENT SELECTION

As with any spinal procedure, proper patient selection is critical in determining PLIF success. While there continues to be some controversy regarding surgical indications, all patients must meet indications for both lumbar decompression and lumbar fusion. There are currently no evidence-based guidelines for choosing PLIF over other posterior or anterior fusion approaches,³⁶ and the surgical indications for PLIF are continually being updated.^{36,37}

Current indications for PLIF include DDD with debilitating low back pain, severe segmental instability, spondylolisthesis, degenerative scoliosis, recurrent disc herniation, pseudarthrosis, and failed back surgery syndrome.^{3,9,13,32,36,38-40} Relative contraindications for PLIF include severe epidural fibrosis with resulting risk of nerve injury, severe osteoporosis, discitis, active infection, adhesive arachnoiditis, severe subchondral sclerosis, severe ankylosis, severe disc space collapse, and conjoined nerve roots restricting access to the disc space.^{3,9,13,32,36-39}

It is critical to ensure that potential patients have undergone several months of conservative therapy unless they present with a focal neurologic deficit. A detailed history, physical examination, and radiographic workup are important in determining the correct diagnosis. It is also important to thoroughly evaluate patients with chronic pain syndromes or psychosocial disorders, as well as those who may be seeking compensation or litigation, as it has been shown that these patients have worse outcomes following surgery.⁴¹⁻⁴⁴ Important diagnostic imaging studies include lateral flexion-extension radiographs, computed tomography (CT), CT-myelography, and/or magnetic resonance imaging (MRI) (Figs. 70.1 and 70.2). Both CT-myelography and MRI are useful in identifying central or neuroforaminal stenosis, which is commonly seen in cases of DDD and adult spinal deformity. Neuroforaminal stenosis and



Fig. 70.1: A 45-year-old man with low back pain refractory to non-surgical therapy. Sagittal T2 magnetic resonance imaging shows two-level disc disease.

associated radicular pain can be particularly difficult to alleviate without correcting the associated degenerative deformity when present.

■ OPERATIVE TECHNIQUE

The fundamental techniques of PLIF are to (1) remove the degenerated disc materials and thoroughly clean the endplates from cartilaginous layers; (2) insert the cage without damaging the bony endplates; (3) select appropriately sized cages; and (4) apply adequate compressive force with the pedicle screws to the disc space in order to stimulate fusion.²

Positioning

Open PLIF is performed with the patient placed in the prone position on a Jackson table or with chest rolls on a Wilson frame. Intra-abdominal pressure should be minimized to avoid venous engorgement, stasis, and epidural venous bleeding. The patient is prepped and draped in the standard sterile fashion.

Exposure

Intraoperative X-rays are obtained to confirm the proper level prior to making the skin incision. Once the skin incision is made, it is taken down to the lumbosacral fascia, which is opened in the midline. A subperiosteal dissection is then performed in the usual manner. It is important to

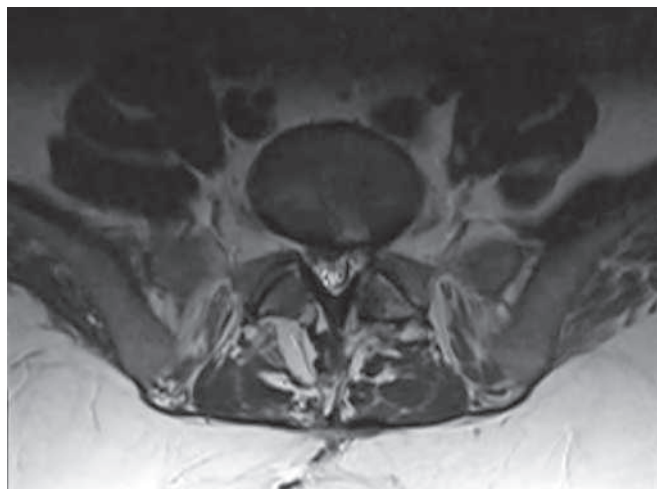


Fig. 70.2: Axial T2 magnetic resonance imaging shows bulging degenerative disc with canal compromise.

extend the dissection laterally beyond the border of the pars and articulating facet joints. In order to minimize blood loss and postoperative pain, the transverse processes do not need to be exposed, unless transverse process fusion is planned in addition to PLIF.

After radiographic verification of the correct level, interlaminar decompression is performed to achieve adequate exposure of the disc space. It is at the surgeon's discretion whether a partial or full facetectomy is performed. We prefer to remove the entire facet joint to maximize exposure for intervertebral graft placement with minimal neural retraction. Complete facetectomy is performed when transpedicular instrumentation will be used.

Depending on the amount of bone that needs to be removed for adequate decompression, either a laminotomy or full laminectomy is performed. We prefer to perform a full laminectomy and remove the spinous processes in order to keep the thecal sac under direct visualization and make retraction safer, but this is not required for interbody fusion. Gentle retraction of the nerve roots and thecal sac allows identification and proper coagulation of the epidural venous plexus over the dorsal annulus in order to maintain a dry operative field.

Discectomy

With careful nerve root retraction, a No. 15 blade is used to incise the annulus widely. Starting with a 7 mm intradiscal shaver, the disc space is entered from one side with the shaver parallel to the endplates and is then rotated

several times. Intradiscal shavers have side cutting edges, which remove both disc and the endplates. Using progressively larger shavers on alternating sides will allow for distraction of the disc space and aggressive removal of disc material bilaterally. Removing as much of the dorsal disc material as possible will provide a sufficient area of bone contact between the vertebral bodies and grafts, thus maximizing the likelihood of fusion. It is also critical to remove the cartilaginous end plates down to the level of cortical cancellous bone to ensure there is adequate blood supply for interbody fusion.⁴⁵



Fig. 70.3: Postoperative computed tomography shows placement of two polyetheretherketone cages. Note bone chips in disc space.

Grafting and Instrumentation

Once the disc space is adequately prepared, the chosen graft material is placed. Posterior lumbar interbody fusion with transpedicular instrumentation is more common than non-instrumented PLIF techniques, because instrumentation has been shown to decrease postoperative complications such as pseudarthrosis, graft displacement, and progressive kyphosis.^{46,47} Therefore, PLIF with transpedicular instrumentation will be the method discussed in this section.

Even with transpedicular instrumentation, autologous cancellous bone cannot be used as an interbody graft by itself, as it does not have the mechanical strength required to maintain the disc height. Either a corticocancellous graft or an intervertebral fusion device is required to supply sufficient vertebral column support postoperatively (Fig. 70.3). Regardless of the implant chosen, it must provide a proper fit. The dorsal portion of the graft should be shaped in a curvilinear fashion to correspond with the adjacent vertebral bodies and should be placed so that it is 5 mm ventral to the spinal canal.

Once the graft has been placed, all distracting instruments are carefully removed to allow the fusion segment to compress to help prevent bone graft extrusion. At this point, all neural elements should be checked to ensure they are fully decompressed. Interpedicular instrumentation is then performed to immobilize the spine and to provide compression loading of the bone graft between the well-vascularized vertebral bodies in order to stimulate bone fusion according to Wolff's law⁴⁸ (Figs. 70.4 to 70.8).



Fig. 70.4: Sagittal X-ray 2 years after surgery shows solid fusion with restoration of height and lordosis.



Fig. 70.5: Anteroposterior X-ray shows two-level solid fusion.



Fig. 70.6: A 65-year-old woman with neurogenic claudication and back pain. Magnetic resonance imaging shows degenerative spondylolisthesis and severe stenosis.



Fig. 70.7: Postoperative lateral X-ray shows improvement in lordosis. Patient's pain is resolved.



Fig. 70.8: Postoperative anteroposterior X-ray shows adequate cage placement and restoration of disc height.

COMPLICATIONS

Several types of complications can occur following initial PLIF surgery, primarily due to the challenging nature of the procedure. These complications run the gamut from mildly annoying to potentially devastating and can occur in up to 37.5% of cases.^{9,49} The overall reported complication rates of PLIF range from 8% to 80%,^{3,11,13-16,39,50-52} due to reporting variations.³

The complications commonly associated with open PLIF are intraoperative neurologic injury, interbody implant or bone graft migration, dural tear, infection, heterotopic

ossification, postoperative radiculopathy, osteolysis, and subsidence.³ Other complications associated with open PLIF are symptomatic atrial septal defect, intervertebral disc space collapse with resultant neuroforaminal stenosis, segmental instability or pseudarthrosis, increased blood loss, prolonged operating time, more extensive dissection, and a higher intraoperative complication rate.^{6,8} Postoperative infection has been reported in up to 9% of patients,^{3,11,13,39,50,52} the risk of which may be reduced by perioperative antibiotics, limited soft tissue dissection, and shortened surgical time.³ Incidental dural tears are among the most common iatrogenic injuries during open PLIF, with an incidence of 2–14%.^{3,13,15,39,50,52} Incidental durotomy increases operative time, blood loss, and length of hospital stay.^{3,53}

One of the most serious complications associated with PLIF is postoperative neurologic deficit, with incidence rates ranging from 9% to 24.6%.^{9,36,49} Postoperative neurologic complications include paresthesias, unrelenting pain, or neurologic deficit, and often occur if the exiting nerve root is over-retracted during graft placement. Radicular pain is the most commonly reported symptom of intraoperative neurologic injury.^{3,11,15,50,52} The incidence of neurologic complications can be reduced by removing more bone to facilitate graft insertion and meticulously protecting the nerve during interbody preparation and implant placement. We often place a freer or other instrument between the nerve and the graft or cage when it is tapped into the disc space.

Any posterior lumbar surgery may result in complications, and these include dural tear with or without cerebrospinal fluid leak, pedicle screw malplacement and/or breakage, wound infection requiring antibiotics and/or debridement, postoperative hematoma, prolonged pain, anesthetic problems, iliac artery injury, increased blood loss, arachnoiditis, iliac crest bone harvest site pain, delayed wound healing, intraoperative pedicle fracture, pulmonary embolism, cerebellar infarction or hemorrhage, or epidural fibrosis or scarring.^{9,21,31,36}

Additional challenges in performing PLIF are achieving solid fusion, as well as restoring disc space height and lordosis. Pseudarthrosis can occur if there is not enough appropriate graft material. The gold standard for grafting has been autologous iliac crest bone; however, the harvesting procedure has its own set of complications, including nerve injury, chronic pain, and a dearth of bone. Alternatives to iliac crest bone graft include allograft, local autograft, demineralized bone matrix, or recombinant bone morphogenetic protein (rhBMP). These materials are often morselized and placed in a cage, usually polyetheretherketone, before the graft is inserted into the disc space. We often place autograft into the disc space before cage placement to enhance the likelihood of fusion. We use lordotic spacers to restore proper disc space alignment, and distract the disc space with pedicle screws to allow for the largest possible graft to be placed. The graft is then loaded in compression. Graft or cage migration, subsidence, and disc space collapse can potentially be avoided by proper preparation of the endplates, appropriate graft size and shape, and the use of pedicle screws.

The use of rhBMP to achieve interbody fusion has increased in the past several years. Recombinant bone morphogenetic protein used in PLIF is currently off-label,⁵⁴ but has been shown to facilitate bone growth and fusion.^{3,9,14,16,17,51} The optimal dosage of BMP in PLIF remains elusive.³ In patients undergoing PLIF with BMP, complications have included radiculitis, ectopic bone formation, osteolysis, and poorer global outcomes.^{3,55} Ectopic bone formation outside the disc space and into the spinal canal may lead to possible radicular complaints.^{56,57}

MINIMALLY INVASIVE APPROACHES

In the past several years, there has been an increased interest in minimally invasive PLIF.

This procedure offers several potential advantages, including less tissue dissection, decreased surgical site infections, less postoperative pain, less blood loss, shorter

hospital stays, and earlier return to work.^{9,58-62} These advantages appear to be related to the decreased tissue dissection.³ Indications for minimally invasive PLIF are the same as for open PLIF. Overall outcomes appear to be similar to those of open PLIF,⁶²⁻⁶⁵ but further long-term data is needed. Minimally invasive PLIF can be challenging due to the smaller work space and limited visualization. Reported complications include neurologic injury, increased reoperation rate, implant migration, and pseudarthrosis.^{3,52,61,62}

In the minimally invasive approach, the patient is placed prone and fluoroscopy is used to determine the correct operative level. A short vertical incision is made in the paraspinal area. A Steinman pin and serial dilators are used to perform the muscle splitting. After appropriate muscle dissection has been performed, a tube is attached to the flexible table-mounted arm and the dilators are removed. The laminotomy and discectomy are performed through the tube in a fashion similar to an open discectomy. End-plate preparation can be performed with curettes and rasps, and then the disc space can be distracted with the trial sizers. Bone chips can then be placed in the disc space, and the interbody graft device is tapped into place. Final placement can be assessed with fluoroscopy. Fluoroscopy is also used to place percutaneous pedicle screws. The pedicles are cannulated with a needle and then tapped into place. A K wire is then placed in the pedicle, with removal of the needle. A tap can be placed over the K wire into the pedicle, and then pedicle screws are advanced into the vertebral body. Proper position is verified with anteroposterior and lateral fluoroscopy. Rods are then placed and tightened with screw caps (Figs. 70.9 to 70.11).



Fig. 70.9: A 41-year-old woman with low back pain and L4-L5 spondylolisthesis. Patient underwent minimally invasive L4-L5 posterior lumbar interbody fusion.



Fig. 70.10: Intraoperative fluoroscopy shows cage placement before tube is removed.

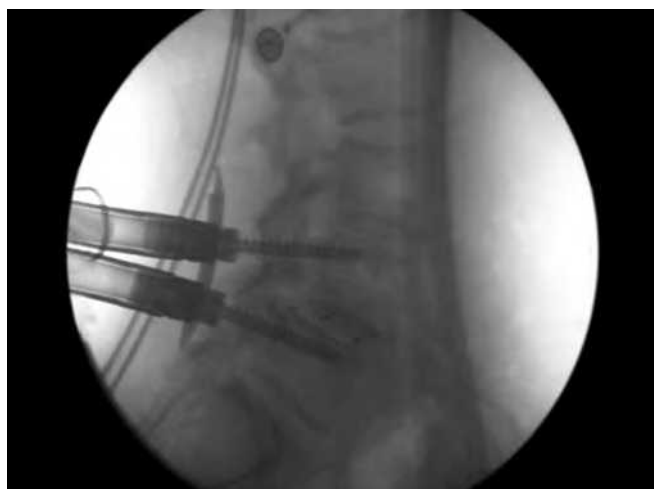


Fig. 70.11: Intraoperative X-ray shows placement of cage and percutaneous pedicle screws.

CONCLUSION

Careful patient selection and meticulous surgical techniques are critical to PLIF success. While PLIF continues to be a technically demanding procedure, recent improvements in surgical techniques and interbody implants have led to impressive fusion rates with excellent patient outcomes.

KEY POINTS

- Proper patient selection is critical in determining PLIF success. Current indications for PLIF include DDD with debilitating low back pain, severe segmental instability, spondylolisthesis, degenerative scoliosis, recurrent disc herniation, pseudarthrosis, and failed back surgery syndrome.
- The fundamental techniques of PLIF are to remove the degenerated disc materials and thoroughly clean the endplates from cartilaginous layers, insert the cage without damaging the bony endplates, select appropriately sized cages, and apply adequate compressive force with the pedicle screws to the disc space in order to stimulate fusion.
- Posterior lumbar interbody fusion with transpedicular instrumentation is more common than noninstrumented PLIF techniques, because instrumentation has been shown to decrease postoperative complications such as pseudarthrosis, graft displacement, and progressive kyphosis.

- Even with transpedicular instrumentation, autologous cancellous bone cannot be used as an interbody graft by itself, as it does not have the mechanical strength required to maintain the disc height. Either a corticocancellous graft or an intervertebral fusion device is required to supply sufficient vertebral column support postoperatively.
- Several types of complications can occur following initial PLIF surgery, primarily due to the challenging nature of the procedure.
- In the past several years, there has been an increased interest in minimally invasive PLIF. This procedure offers several potential advantages, including less tissue dissection, decreased surgical site infections, less postoperative pain, less blood loss, shorter hospital stays, and earlier return to work.

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Transforaminal Lumbar Interbody Fusion

Takashi Tsuji

Snapshot

- » Indications
- » Surgical Technique
- » Graft Materials for Interbody Fusion
- » Clinical Results

INTRODUCTION

Different procedures of spinal fusion have been developed since Albee FH and Hibbs RA first reported on posterior fusion in 1911. Over the years, there have been differing opinions among surgeons as to appropriate procedures to use for various spinal etiologies. Lumbar fusion surgery is being performed with increasing frequency, particularly for the treatment of degenerative diseases. Concurrently, lumbar interbody fusion techniques have been refined, and the surgeon now has a number of treatment options with regard to instrumentation, bone graft material, and surgical approach.^{1,2}

Posterior lumbar interbody fusion (PLIF) after lumbar disc removal was first reported by Jaslow³ in 1946. The “father” of PLIF, however, was believed to be Cloward.⁴ Although PLIF requires only one surgical approach, it is associated with significant retraction on the thecal sac and nerve roots, with the attendant potential for root injury.^{1,5} Unfortunately, PLIF is also limited to the lower lumbar spine (L3-S1) owing to the risk of damage to the conus medullaris at higher levels. In 1982, Harms and Rolinger⁶ suggested the placement of bone graft and titanium mesh cage, via a transforaminal route, into disc space that previously had been distracted using pedicle screw instrumentation [transforaminal lumbar interbody fusion (TLIF)]. This approach can be accomplished without exposing more than the unilateral foramen, and retraction on the thecal sac is minimal. This approach also can be particularly advantageous in the face of scarring tissue after prior surgery.

INDICATIONS

Like PLIF, TLIF is a single-stage posterior procedure that achieve stable three-column fixation. Unlike PLIF, however, TLIF requires exposing only the unilateral neural foramen (although bilateral decompression can be performed if needed) and since a complete facetectomy is performed, less neural retraction is required which leads to a lower incidence of dural or neurologic injury.⁷ Consequently, TLIF can be performed safely above L3 with minimal risk of conus injury and is better suited for reoperations with significant epidural fibrosis because only a one-sided, lateral dural exposure is needed.^{8,9} However, one potential disadvantage of TLIF technique is that by performing a total facetectomy, the spine is significantly destabilized. Thus, posterior fixation, typically using bilateral pedicle screw, is mandated to keep the adequate stability.

Transforaminal lumbar interbody fusion is currently performed for the following conditions: low-grade spondylolisthesis, degenerative disc disease, discogenic low back pain, recurrent lumbar disc herniation associated with significant mechanical back pain, foraminal stenosis and radiculopathy, lumbar deformity, and multiply-operated lumbar spine.

SURGICAL TECHNIQUE

The patient is placed in the prone position with fully extended hip joints and legs on a four-poster frame to maintain lordosis throughout the procedure. It is important to

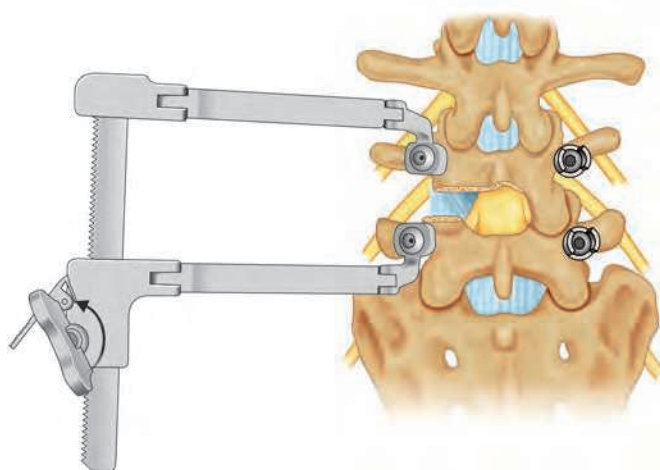


Fig. 71.1: Laminectomy, unilateral facetectomy, or both are performed, depending on the clinical situation. Using the distraction device across the pedicle screw construct nerve roots, thecal sac, and disc space can be easily visible.

allow the abdomen to hang free and to allow positioning for appropriate radiographs. Bilateral subperiosteal dissection is extended just lateral to the facet joints through a midline posterior approach, and the facet capsules are denuded with electrocautery.

A laminectomy, unilateral facetectomy, or both are performed, depending on the clinical situation. Minimally, a unilateral laminotomy and partial facetectomy are performed on the more symptomatic side. A complete facetectomy is not always necessary. In cases requiring more medial decompression, a medial facetectomy is sufficient for exposure. In cases not requiring medial decompression, exposure is obtained by removing the lateral aspect of the inferior articular facet to the point at which the edge of the thecal sac is visualized. Following the placement of segmental pedicle screws, distraction across the pedicle screw-rod construct is performed which allows for easy visualization of the nerve roots, thecal sac, and disc space (Fig. 71.1).

The disc is incised with a no. 15 blade and removed with a rongeur, and then the posterior lip of each endplate is removed with the use of an osteotome, while carefully protecting the thecal sac and nerve roots. This facilitates complete removal of the cartilaginous endplate and more extensive disc excision. Ringed curettes or osteotomes are used to remove disc material from the vertebral endplate. Extreme care is taken reaching across to the contralateral disc area. Harvested local bone combined with or without iliac crest autograft is packed anteriorly in the disc space.

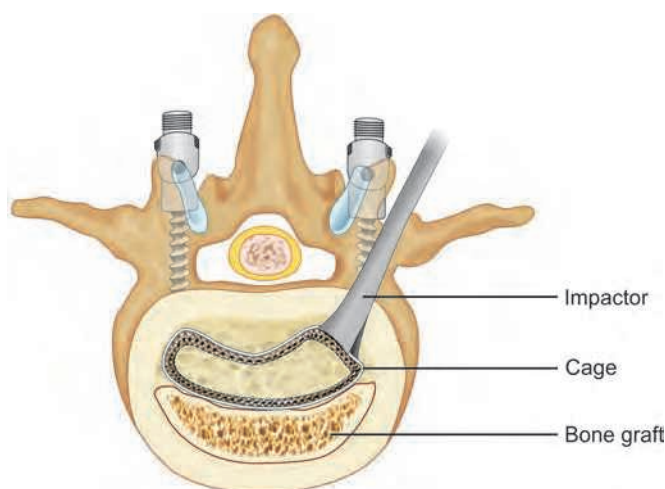


Fig. 71.2: Harvested local bone and intervertebral cage are packed anteriorly in the disc space and directed across to the contralateral disc space.

The intervertebral cage or spacer is then placed and directed across to the contralateral disc space, and if necessary, a second spacer is then placed on the side of the approach (Fig. 71.2).

After the interbody construct is placed, the pedicle screws are attached to and compressed on the rod, thereby restoring lumbar lordosis while maintaining the restored disc height (Fig. 71.3).

Postoperatively, a custom orthosis is worn for 3 months. Patients are encouraged to walk as early as the first postoperative day.

GRAFT MATERIALS FOR INTERBODY FUSION

Following a complete discectomy, a structural spacer filled with osteoinductive graft material should be placed into the interbody space in order to maintain intervertebral body height, lumbar lordosis, and sagittal balance.

Current options for interbody spacers include titanium cages, carbon fiber cages, polyetheretherketone cages or absorbable cages.

CLINICAL RESULTS

The goals of TLIF are to relieve pain and neural compression in conjunction with achieving a stable arthrodesis. From a biomechanical perspective, TLIF offers all of the same expected benefits of PLIF. Biomechanical analysis



Fig. 71.3: Postoperative X-ray.

has demonstrated that >30% of the vertebral endplate surface area is required to achieve rigid interbody fusion,¹⁰ and in vivo clinical study has demonstrated that 69% disc volume excision (56% of endplate surface area) can be achieved through a unilateral transforaminal approach.¹¹ Thus, TLIF can provide adequate surface area for solid interbody fusion.

There are many evidences supporting the efficacy of the TLIF technique. Potter et al. prospectively analyzed 100 consecutive patients with degenerative lumbar disease treated with TLIF with bilateral pedicle screw fixation. They concluded that TLIF is a safe and effective method of achieving lumbar fusion with a 93% radiographic fusion success and a nearly 80% rate of overall patient satisfaction, but frequently results in incomplete relief of symptoms.¹² Yan et al. compared the therapeutic effect of PLIF and TLIF with pedicle screw fixation on treatment with 187 patients with degenerative spondylolisthesis, and concluded that interbody fusion with either a PLIF or a TLIF technique provides equivalent pain relief or functional outcomes in the treatment of degenerative spondylolisthesis.¹³

Tormenti et al. analyzed perioperative complication rates of 531 TLIF procedures at a large academic medical center using institution's complication database or the medical record.¹⁴ One hundred thirty-five patients (25.4%) had at least one procedure-related complication. The most common complications were durotomy (14.3% of patients) and infection (3.8% of patients). The overall complication rate was greater in those patients who had undergone a previous operation (OR 1.75, 95% CI 1.18–2.59; $P < 0.01$) and in those who had multilevel surgery (OR 1.54, 95% CI 1.04–2.28; $P = 0.03$). Moreover, Khan et al. reported

perioperative complications in patients undergoing TLIF as a revision surgery.¹⁵ They concluded, in the hands of experienced surgeon, that revision open TLIF does not necessarily increase the risk of perioperative complications compared with primary TLIF. Two or more previous lumbar decompressive procedures, however, increase the risk of inadvertent dural tears and neural injury.

Minimally invasive techniques for TLIF (MIS TLIF) have recently been introduced with the aim of smaller wounds, less tissue trauma, and faster recovery. Lee et al. performed prospective cohort study to compare the clinical and radiological outcomes of single-level open versus MIS TLIF.¹⁶ One hundred forty-four single-level open and MIS TLIF were performed with 72 patients in each group. At 6 months and 2 years, clinical outcome analysis showed both groups improving similarly in terms of visual analog scale (VAS), Oswestry disability index (ODI), short form 36-item health survey (SF-36), return to full function, and patient rating. However, MIS patients have less intraoperative blood loss, needed less morphine, and were able to be discharged from hospital earlier ($P < 0.05$). Therefore, the MIS TLIF provides similar clinical and radiological outcomes with additional benefits of less perioperative blood loss and pain, and a shorter hospital stay.

SUMMARY

Transforaminal lumbar interbody fusion can be performed with acceptable risk and will result in a satisfactory outcome using a single posterior approach. Complications are generally minor and transient in nature. In spite of this, patients may have residual symptoms postoperatively, indicating a need for detailed preoperative evaluation and rigorous patient selection.

KEY POINTS

- Transforaminal lumbar interbody fusion is a single-stage posterior procedure that achieve stable three-column fixation.
- Transforaminal lumbar interbody fusion exposes only the unilateral neural foramen; since a complete facetectomy is performed, less neural retraction is required, thereby leading to a lower incidence of dural or neurologic injury. Consequently, TLIF can be performed safely above L3 with minimal risk of conus injury and is better suited for reoperations because only a one-sided, lateral dural exposure is needed.

- In vivo clinical study has demonstrated that 69% disc volume excision (56% of endplate surface area) can be achieved through a unilateral transforaminal approach.
- Interbody fusion with either a TLIF technique or a PLIF technique provides equivalent pain relief or functional outcomes in the treatment of degenerative disease.
- Transforaminal lumbar interbody fusion can be performed with acceptable risk and will result in a satisfactory outcome using a single posterior approach. Complications are generally minor and transient in nature.

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Lateral Lumbar Interbody Fusion Techniques: Degenerative and Scoliotic

Todd Lansford, Murat Pekmezci, Vedat Deviren

Snapshot

- » Evolution of Lateral Lumbar Interbody Fusion
- » Indications
- » Preoperative Workup
- » Lateral Lumbar Interbody Fusion Technique

INTRODUCTION

Normal aging results in decreased proteoglycan content of the disc nucleus resulting in a drop in nucleus pressure. When there is disc degeneration, there is also structural damage to disc matrix and increased activity of the matrix degrading enzymes. These changes lead to loss of disc height and bulging of the annulus radially, creating a slack of the collagen fibers of the outer annulus and intervertebral ligaments—overall resulting in segmental instability. The natural response to this increased mobility and radial bulging of the disc is the formation of vertebral body osteophytes that reconstitutes segmental stability by limiting bending motion (Adams, 2006, Spine). When these osteophytes are formed on the posterolateral aspect of the vertebral body, they can encroach on the foramen in association with the bulging disc resulting in foraminal stenosis. As disc degeneration and height loss progress, there is also a shift in the compressive load bearing from the vertebral body to the posterior arch. Normally, only 25% of the load is transferred through the posterior column; however, with progressive disc degeneration, this increases up to 50% (Robson-Brown). The stress concentration in the facet joints results in cartilage loss and osteoarthritis of the posterior elements. Osteophytes arising from the facet joints would also contribute to the foraminal/lateral recess stenosis. As the disc decreases in height, it would also result in up-down stenosis at the foramen between the pedicles. In addition, ligamentum

flavum will buckle into the spinal canal resulting in central stenosis and neurogenic claudication. As the osteoarthritis of the facet joints progresses, their ability to withstand shear forces would decrease and spondylolisthesis may develop. Increased load-bearing by the posterior elements would result in stress shielding of the anterior aspect of the vertebral bodies, ultimately decreasing bone density in this region and leading to potential fractures when load is transferred back to the anterior column (Adams, 2006). Facet joints often show left-right asymmetries that can lead to abnormal axial rotation and lateral bending movements resulting in degenerative scoliosis. Asymmetric vertebral compression fractures can also contribute to the deformity. In summary, degenerative disc disease can result in a variety of clinical scenarios ranging from radiculopathy to degenerative scoliosis with sagittal and coronal imbalance. Understanding the underlying pathophysiological processes would enable one to select treatment strategies that would be able to correct the resulting deformities and decompress the neural structures in a much efficient manner.

The conservative treatment options range from medical management, physical therapy to epidural/transforaminal steroid injections, and should be exhausted first. The surgical interventions for these degenerative disorders aim to correct the deformity, decompress the neural elements, and, finally, stabilize the spine through arthrodesis (Tanaka). These goals can be achieved through all anterior, all posterior, or often combined approaches.

Posterior approaches have been the workhorse of lumbar spine surgery. It is familiar to spine surgeons, allows direct decompression of the canal by excising the redundant ligamentum flavum and foramen by undercutting of the facet joints, and achieves arthrodesis via laying bone graft between the transverse processes. However, in the setting of severe loss of disc height, up-down stenosis at the foramen cannot be addressed unless the disc height is restored through an interbody fusion. Addressing anterior column has two important implications. First, it would allow restoration of the lost disc space height that would cause decompression of the foramina and decompression of the spinal canal by tensioning and eliminating the buckling of the ligamentum flavum. Second, it will increase the rate of successful arthrodesis as anterior interbody fusion has better vascularity and increased surface area for fusion. Interbody fusion can be achieved via direct anterior lumbar interbody fusion (ALIF) or lateral lumbar interbody fusion (LLIF) methods or indirect posterior or transforaminal lumbar interbody fusion (TLIF) methods. In treatment of adult degenerative scoliosis, the posterior approaches are again more familiar to the spine surgeon; however, deformity correction and indirect decompression of the neural elements are inferior to anterior approaches. The interbody devices are smaller in size and engage the center of the endplate with a higher risk of subsidence and loss of correction. Besides, preparation of the disc space and insertion of the interbody device require extensive nerve and dural manipulation, which may lead to neurologic deficits and dural tears. Removal of the lamina and partial/complete facetectomies essentially leave only the transverse processes to achieve arthrodesis that is traditionally associated with lower fusion rates. On the other hand, anterior approaches give significant advantages to the surgeon by restoration of the disc height resulting in indirect decompression of the foramen, by addressing up and down stenosis, and canal, by stretching the buckled ligamentum flavum (Lund). In addition, lengthening the anterior column easily treats the sagittal plane deformity. The big surface area between the endplates provides an excellent environment to achieve arthrodesis. However, anterior approaches also have disadvantages such as requiring an approach surgeon in the United States, excessive dissection, and potential intraabdominal as well as abdominal wall morbidity (Bridwell). Ileus is a common postsurgical issue, with bowel injury a real possibility. Vascular injuries are rare, but sometimes life-threatening. When addressing L5-S1, injury to the superior

hypogastric plexus may lead to retrograde ejaculation that may cause significant morbidity, especially in the younger male patients. Finally, combined procedures allow best of both worlds as anterior procedures allow restoration of disc height, deformity correction, and solid arthrodesis; on the other hand, posterior procedures allow more directed decompression and additional stability to maintain correction and prevent subsidence. However, combined approaches expose patients to surgical procedures, further increasing the risk of complications. Therefore, there was an obvious need for less invasive techniques that would enable the surgeon accomplish the same result with fewer complications.

■ EVOLUTION OF LATERAL LUMBAR INTERBODY FUSION

In order to address the concerns of the conventional anterior approach while still achieving the benefits of full anterior column utilization, Pimenta presented the lateral transpsoas approach in 2001 (Ozgur). This technique eliminates the need to mobilize the vessels and, furthermore, eliminates the need for the approach surgeon. It is a true anterior retroperitoneal approach to the lumbar spine from L1 to L5 through the psoas muscle. At higher levels, it allows access up to T5 via a retropleural or transthoracic approach. This direct access to the anterior column still allows the ability to perform an extensive discectomy, particularly releasing the main deforming forces by releasing the annulus on the lateral aspect of the disc. This method has two key technical features that separate it from the conventional ALIF. First, it preserves the anterior longitudinal ligament that allows deformity correction via ligamentotaxis and stability as the interbody cage is kept in place by the tightened anterior longitudinal ligament (ALL) and posterior longitudinal ligament (PLL). Second, as the interbody cage is inserted via a lateral approach, it can span the ring apophysis with a larger footprint cage, both decreasing the risk of subsidence and increasing the potential for successful fusion. The minimally invasive nature of this approach would also allow decreased operative times and blood loss.

Complications associated with the lateral transpsoas approaches may be categorized as neural, visceral, and vascular. This approach requires placement of a retractor through the psoas muscle, where the lumbosacral plexus lies. These nerves run within and around the psoas and are not easily visible. Therefore, they are indirectly monitored and protected through a special neuromonitoring sys-

tem that provides real-time feedback on their position in the field. Hence, knowledge of the anatomy of these structures including the genitofemoral nerve is vital to avoiding their injury. Moro et al. studied the configuration and noted that above L4-L5, these nerves were at the posterior quarter of the vertebral body. At L4-L5, they cross more anteriorly into the middle-posterior quarter of the vertebral body. This translation may be further increased in the setting of spondylolisthesis, where translating cephalic segment would move the plexus more anteriorly. In addition, anatomic anomalies are seen in up to 20% of patients (Samudrala). The genitofemoral nerve has the most variations in its path as it courses in a tangential manner piercing the psoas near L3-L4. Genitofemoral injury has been reported, with patients experiencing transient post-op groin pain (Bergey). With such possible variability in the course of these nerves, there is a real possibility of complications. The most common side effect following a transpsoas approach is transient hip flexor weakness (up to 27.5%) (Tohmeh), which is believed to be a consequence of trauma to the psoas muscle itself, rather than a neural injury. Distal motor deficits (e.g. quadriceps weakness) have been reported at an incidence of 0.7–3% (Rodgers, Tohmeh). Avoidance is based on meticulous dissection along with proper neuromonitoring using free-run and triggered electromyography (EMG) (Tohmeh, Uribe).

By limiting mobilization of the peritoneal contents and vascular structures, risk of visceral and vascular injury is significantly reduced compared with a direct anterior approach. However, the risk is nonzero; the vessels continue to lie close to the surgical field; and there are reports of bowel injury (Tormenti) in the literature, but incidence over the larger population is uncertain.

■ INDICATIONS

Indications for LLIF are similar to those of any interbody fusion between L1 and L5 and include but are not limited to degenerative disc disease, instability patterns, such as spondylolisthesis (Grade I/II) and postlaminectomy, degenerative scoliosis, recurrent disc herniations, posterior pseudarthrosis, anterior column support, and adjacent segment degeneration. The latter, in particular, is ideal for standalone techniques, which will be discussed below. The lateral approach is particularly useful for revision anterior procedures such as that for failed ALIF and total disc arthroplasty, where scar tissue in the surgical plane may prohibit a secondary anterior retroperitoneal

approach. Historically, this would require a transperitoneal approach with increased risk of complication. In these instances, the transpsoas approach avoids the scarred-in plane allowing direct access.

Similarly, limitations for this approach reflect those of any interbody fusion surgery, such as infection. Limitations specific to this procedure would be approaching the L5-S1 disc space as this is not reproducibly accessible due to the iliac crest. High-grade spondylolisthesis, notably at L4-L5, can be challenging secondary to migration of the lumbar plexus anterior with the deformity. Obesity is not as challenging as it may be in ALIF, due to the lateral decubitus positioning of the patient, which allows the abdominal contents and fat to fall forward out of the surgical field.

■ PREOPERATIVE WORKUP

After a detailed history has been obtained, a thorough physical examination should be performed. The radiographic work-up should be the next step and below are a few specifics to the utilization of LLIF.

Standing radiographs are always important for the evaluation of disc height. While magnetic resonance imaging (MRI) is excellent for visualizing the disc and stenosis, it is often done while recumbent and, thus, overestimates the intervertebral disc height. The true height is best seen on radiographs and is critical in evaluating the need for height restoration in the anterior column.

Computed tomography (CT) myelography can be used in place of MRI in cases where patients have had prior surgery with metal implants. Furthermore, it can better detail the sclerosis of the endplates, an important quality in the evaluation of possible standalone constructs. If there are concerns related to bone density in these patients, dual-energy X-ray absorptiometry (DEXA) may be warranted as well.

The information obtained from these diagnostic images can be related to the previously discussed history and physical examination to obtain the diagnosis. With this the treatment plan is set following the indications for the LLIF as described above.

■ LATERAL LUMBAR INTERBODY FUSION TECHNIQUE

The keys to performing LLIF successfully and with minimal complications include careful patient selection, proper positioning, and meticulous surgical technique. Patients are positioned in the lateral decubitus position; an axillary roll is used to minimize the risk of axillary nerve neuropraxia.

To prevent lumbosacral plexus injury, intraoperative monitoring is used. Fluoroscopy is mandatory for real-time spine viewing. Clear anteroposterior (AP) and lateral projections of the lumbar spine must be obtained before the procedure can be performed. The disc space of interest is marked on the lateral fluoroscopy view. It is important at all times to maintain the fluoroscope at 90° to the patient, while also rotating or tilting the table to obtain a true lateral view of the disc. This helps to maintain a straight

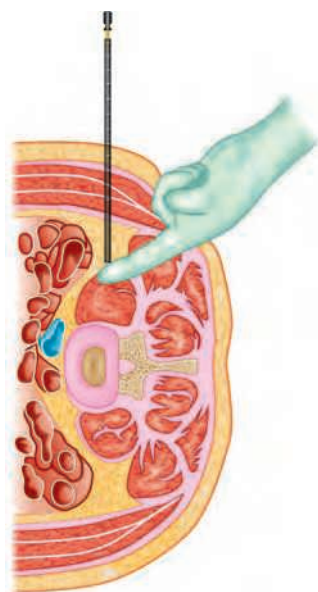
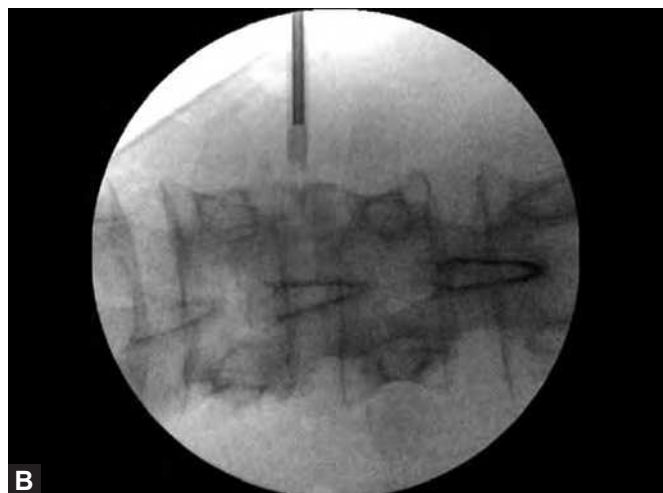


Fig. 72.1: The guidance of the first dilator on to the psoas in the retroperitoneal space through a second posterior incision.

up-down orientation and lateral trajectory of all instruments being passed in and out of the disc. Failure to maintain a strict up-down orientation can result in serious vascular or neurologic injuries caused by inappropriate trajectory. For the direct lateral incision, one may use an oblique incision running parallel to the fibers of the external abdominal oblique musculature. A second posterior incision is used lateral to the border of the erector spinae musculature to introduce a finger bluntly into the retroperitoneal space, open the space, and guide the initial dilators safely to the surface of the psoas muscle (Fig. 72.1). The dilator is advanced through the psoas muscle using dynamically triggered EMG to identify the direction and proximity of spinal nerves relative to the distal end of the dilator. Once it is safely advanced through the psoas muscle, its location is confirmed with lateral fluoroscopy before the placement of a K-wire into the disc space (Figs. 72.2A and B). Subsequent dilators are advanced over the first to separate muscle fibers and widen the exposure, each using dynamically triggered EMG. Then the retractor is placed, and a lateral fluoroscopic image is obtained to ensure that the retractor is in the proper AP location. It is critical that the working zone is not too anterior; it should lie between the posterior and middle-thirds of the lateral disc space projection. The retractor is opened minimally, and a triggered EMG probe is used to stimulate the area to identify any traversing neural elements. If a nerve is seen in the field, it may be gently moved using a Penfield dissector to position it posteriorly behind the retractor. The retractor can be widened independently in the AP and cranial-caudal direc-



Figs. 72.2A and B: The first dilator should be docked on the posterior half of the targeted disc space on the lateral view (A) and flush with the disc on the AP view (B).

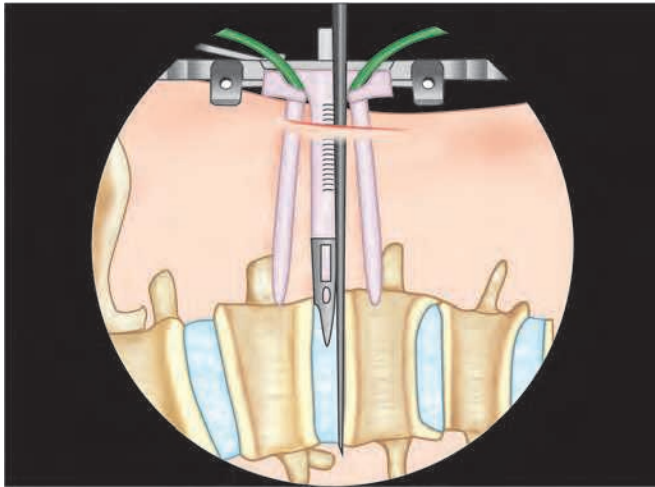


Fig. 72.3: The Cobb is advanced over the endplate on the AP view to the contralateral annulus that is then released by rotating the Cobb.

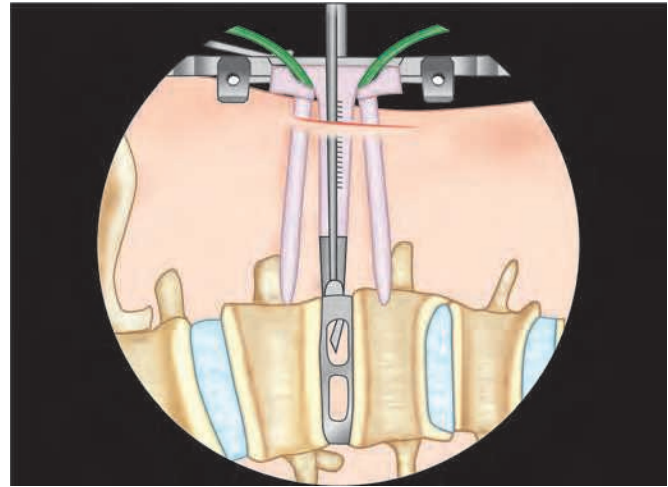


Fig. 72.4: Trials are inserted into the disc space to determine the ideal cage size (width, depth and height).

tions, and care should be taken to expose only as necessary to minimize trauma to the psoas muscle. Once expanded, the location of the anterior vertebral body should be defined by identifying the anterior fiber of the anterior longitudinal ligament. This will help minimize the risks of vascular injury and of anterior graft placement and dislodgment. It is important to continue to reassess the location of the anterior longitudinal ligament during the discectomy procedure.

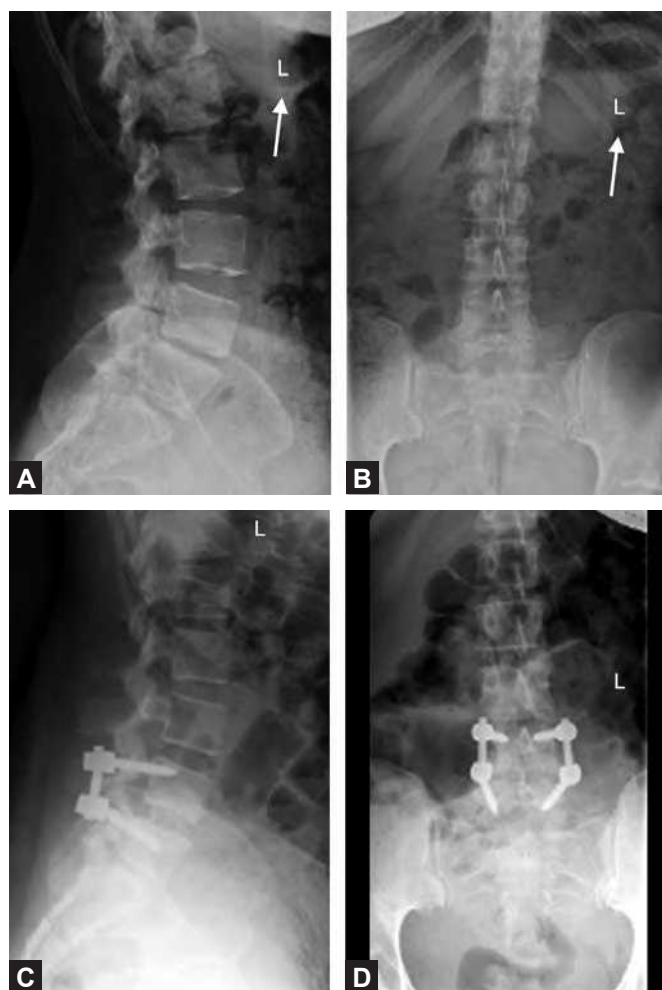
The discectomy is performed using an annular release (Fig. 72.3). Controlled passing of a Cobb elevator is performed across the disc space beyond the contralateral annulus under fluoroscopic guidance. This is done by gently tapping the Cobb across the disc space under fluoroscopic observation. The Cobb is then rotated after it passes through the opposite annulus. In this manner, the contralateral endplate attachment is released. This allows elevation of disc height and attempts deformity correction.

Meticulous care must be taken to avoid endplate violation. Fluoroscopy should be used when spinal instruments, such as curettes, rasps, and Cobb elevators are passed into the disc space. Trials are then introduced serially into the disc space, with care taken not to oversize the graft (Fig. 72.4). A long implant that takes advantage of the biomechanical strength of the dense ring apophysis is recommended. Autologous iliac crest bone graft, or a bone graft replacement, may be placed within the spacer before it is implanted into the disc space. An understanding of the anatomy, vigilant monitoring of the surrounding neurologic structures, a meticulous and thorough discectomy, and appropriate implant placement may minimize complications.

Kepler et al. performed a CT study and demonstrated that LLIF resulted in a 64% increase in the foraminal height and 35% increase in the foraminal area. This is a much better improvement when compared with TLIF/PLIF, where a maximum 30% foraminal height restoration was achieved (Groth).

Treatment of Specific Spinal Conditions

1. *Degenerative disc disease and low-grade spondylolisthesis* (Fig. 72.5): As it was discussed in the previous section, degenerative disc disease and spondylolisthesis are common causes of back pain as well as radicular pain. The classical approach to treat these pathologies has been posterior approaches with pedicle screw fixation. Decompression of the neural elements depends on the removal of ligamentum flavum and osteophytes, and indirect decompression via TLIF/PLIF procedures which is associated with manipulation of the neural elements—all of which potentially increases the risk of injury. Lateral lumbar interbody fusion, on the other hand, allows indirect decompression of the foramen as well as canal, decreasing the need for posterior decompression. Decreasing the need for posterior exposure avoids denervation of the multifidus muscle which is an important factor in the development of adjacent segment disease. Lateral lumbar interbody fusion has also been successfully applied to lumbar spondylolisthesis. Of note, it is indicated only in the low-grade spondylolisthesis, since the risk of injury to the lumbar plexus is significantly higher in the patients with



Figs. 72.5A to D: A 37-year-old man presented with back and leg pain. The radiographic work-up revealed L4-L5 spondylolisthesis (A and B). After failure of nonoperative treatment, he underwent an L4-L5 LLIF, augmented with posterior fixation (C and D)

high-grade (Grades III and IV) spondylolisthesis. First, as the slip gets worse, the overlapping endplate area to place the cage decreases in parallel. Second, the lumbar plexus gradually moves anterior at the lower lumbar levels normally, and, in spondylolisthesis, will be further displaced where it would be difficult to find a safe zone to perform the procedure. Although the same risk still exists with low-grade spondylolisthesis, the reported lumbar plexus injury rate is comparable to degenerative pathologies without an associated slip. Rodgers et al. reported 63 patients with Grade II spondylolisthesis at the L4-L5 level without any neural injuries and all patients went onto union. Marchi et al. reported 52 patients with Grades I and II

spondylolisthesis with majority of the procedures performed at L3-L4 and L4-L5. In 20% of the patients, they reported thigh numbness and/or psoas weakness that was temporary. They did not use any additional instrumentation to support the cage and observed a union rate of 87% and subsidence rate of 17% (Marchi).

Case example: A 37-year-old man presented with back and leg pain. X-rays were taken noting L4-L5 spondylolisthesis (Figs. 72.5A and B). After failure of nonoperative treatment, he underwent an L4-L5 LLIF, augmented with posterior fixation (Figs. 72.5C and D).

2. *Adjacent segment disease following previous lumbar fusion* (Fig. 72.6): Adjacent segment degeneration following lumbar surgery may be observed in up to 35% of the patients (Klopfenstein). The most commonly utilized approach to address this problem is repeat posterior procedures. However, this approach is technically more difficult and associated with higher blood loss, increased risk of infection, dural tear, and pseudarthroses. Lateral lumbar interbody fusion is an attractive alternative in these cases, as the pathology can be addressed directly through a separate approach in a virgin territory. Lateral lumbar interbody fusion will allow restoration of the height of the collapsed/slipped disc, providing indirect decompression of the neural foramen. It can be accompanied with anterior instrumentation to increase the chance of fusion and decrease the risk of subsidence. Klopfenstein et al. reported 14 patients, where they used LLIF to treat a variety of pathologies, such as spondylolisthesis, post-laminectomy instability, and adjacent segment disease. All patients achieved union and 71% had improved radicular symptoms (Klopfenstein).

Case example: After a previous L3-S1 spinal fusion, a 75-year-old woman presented with back and leg pain secondary to adjacent level degenerative disease (Figs. 72.6A and B). She underwent standalone LLIF at L2-L3 (Figs. 72.6C and D).

3. *Standalone constructs—multilevel degenerative disc disease and degenerative scoliosis* (Fig. 72.7): Standalone LLIF application is becoming more widely utilized. It is most often discussed in the treatment of adjacent segment degeneration but is finding promise in most degenerative conditions (Marchi). The main advantage is the elimination of supplemental fixation that would decrease the surgical time and, in return, retraction time, potentially decreasing the risk of injury to the lumbar plexus. Cappuccino et al. demonstrated that when a



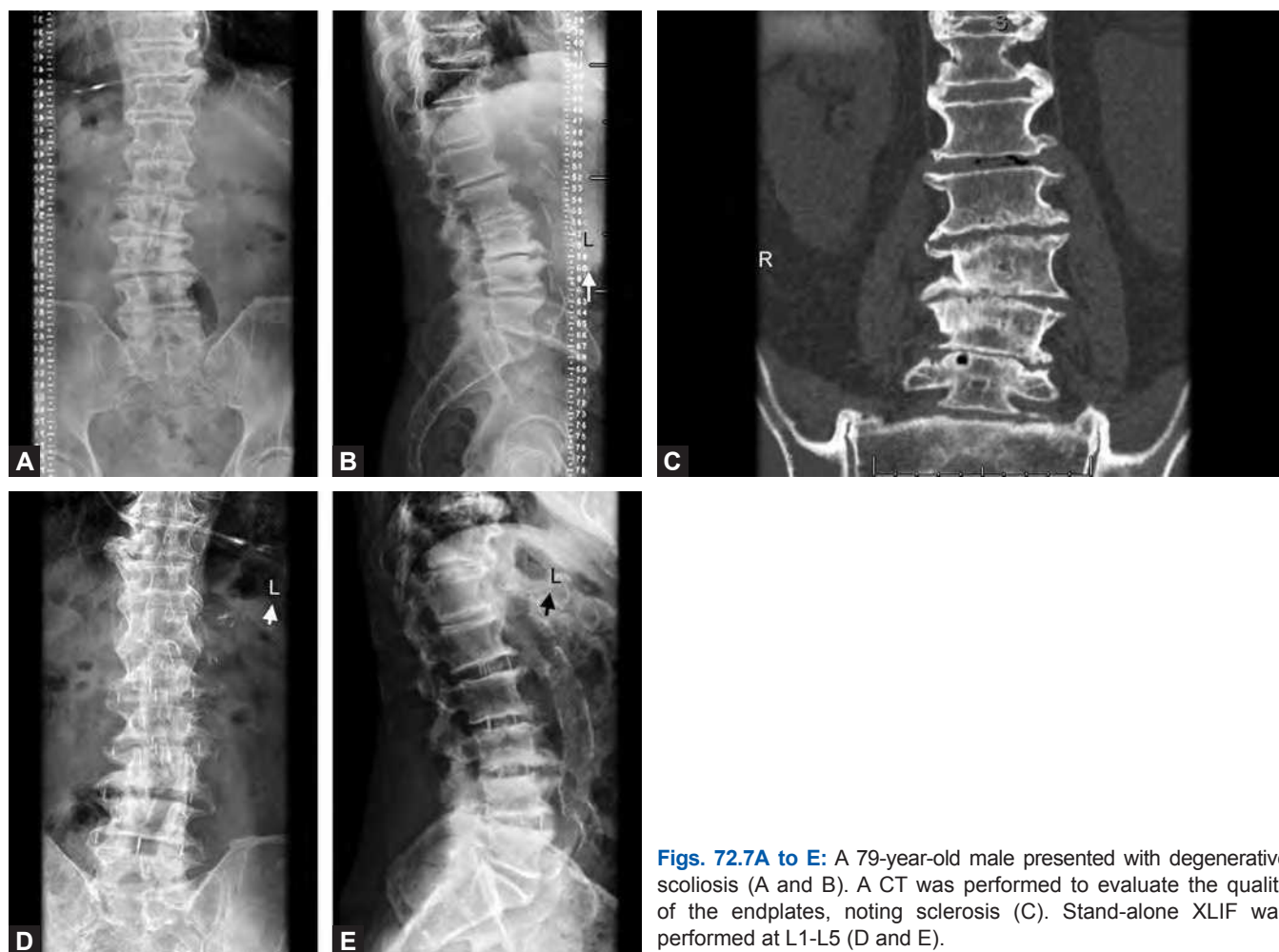
Figs. 72.6A to D: Following a previous L3-S1 spinal fusion, a 75-year-old woman developed adjacent level degenerative disease, presenting with back and leg pain (A and B). She underwent standalone LLIF at L2-L3 (C and D).

cage with big footprint is used and once it has a snug fit between the tensioned ALL and PLL, there has been a 70% decrease in the flexion-extension and lateral bending motion at the instrumented site. Addition of a lateral plate or a pedicle screw decreased the motion for an additional 10–15% (Cappuccino). It is assumed that as the degenerative cascade progresses, the arthritic changes in the facet joints will limit the ROM at the affected segment further. When combined with the anterior cage, the treated segment will hypothetically have adequate rigidity to achieve fusion. Marchi et al. reported 87% union rate with this technique. However, there was a 17% rate of high-grade subsidence, half of which required additional procedures to achieve a rigid fixation (Marchi). First and foremost, surgical technique is key to decrease the risk of this complication. Preservation of the endplates is critical, as is proper preparation to utilize the correct size of implant, maximizing biomechanical spread of force. Also, preoperative evaluation can possibly predict this. The use of DEXA scan will give insight into overall bone quality. Computed tomography scan is routinely obtained to evaluate the endplates themselves. The ideal patient for standalone cases is the patient with advanced facet arthritis, endplate sclerosis, and minimal motion on bending X-rays.

Case example: A 79-year-old man presented with back and bilateral leg pain. X-rays showed degenerative scoliosis (Figs. 72.7A and B). Computed tomography was completed to evaluate endplate, noting sclerosis

(Fig. 72.7C). Stand-alone extreme lateral interbody fusions were performed at L1-L5 (Figs. 72.7D and E). One year after surgery, the patient has continued resolution of symptoms.

4. **Complex deformity and degenerative scoliosis** (Fig. 72.8): The LLIF procedure for treating complex deformity and degenerative scoliosis may offer various clinical advantages over more traditional techniques as noted above. The LLIF procedure straightens and derotates the spine through bilateral annular release, placement of a large implant across the disc space spanning the ring apophysis, and the effects of ligamentotaxis. Segmental interbody implant placement realigns the endplates to a horizontal position, restores disc and foraminal heights, and indirectly decompresses the neural elements. Sagittal balance is also corrected and maintained by placement of an implant, either lordotic or nonlordotic, in the anterior of the disc space. Keshavarzi et al. demonstrated that the majority of the correction in both the coronal and sagittal plane was achieved during the initial LLIF procedure. In addition, the interbody space provides a superior environment for fusion compared with the posterolateral gutter used for posterior approaches. It is frequently used as the first stage of a combined approach. Staging the second posterior approach a couple of days after the LLIF would allow re-evaluating the patients to see if they need posterior decompression. Often, indirect decompression that was provided by the LLIF may eliminate the need to perform additional posterior decompression.

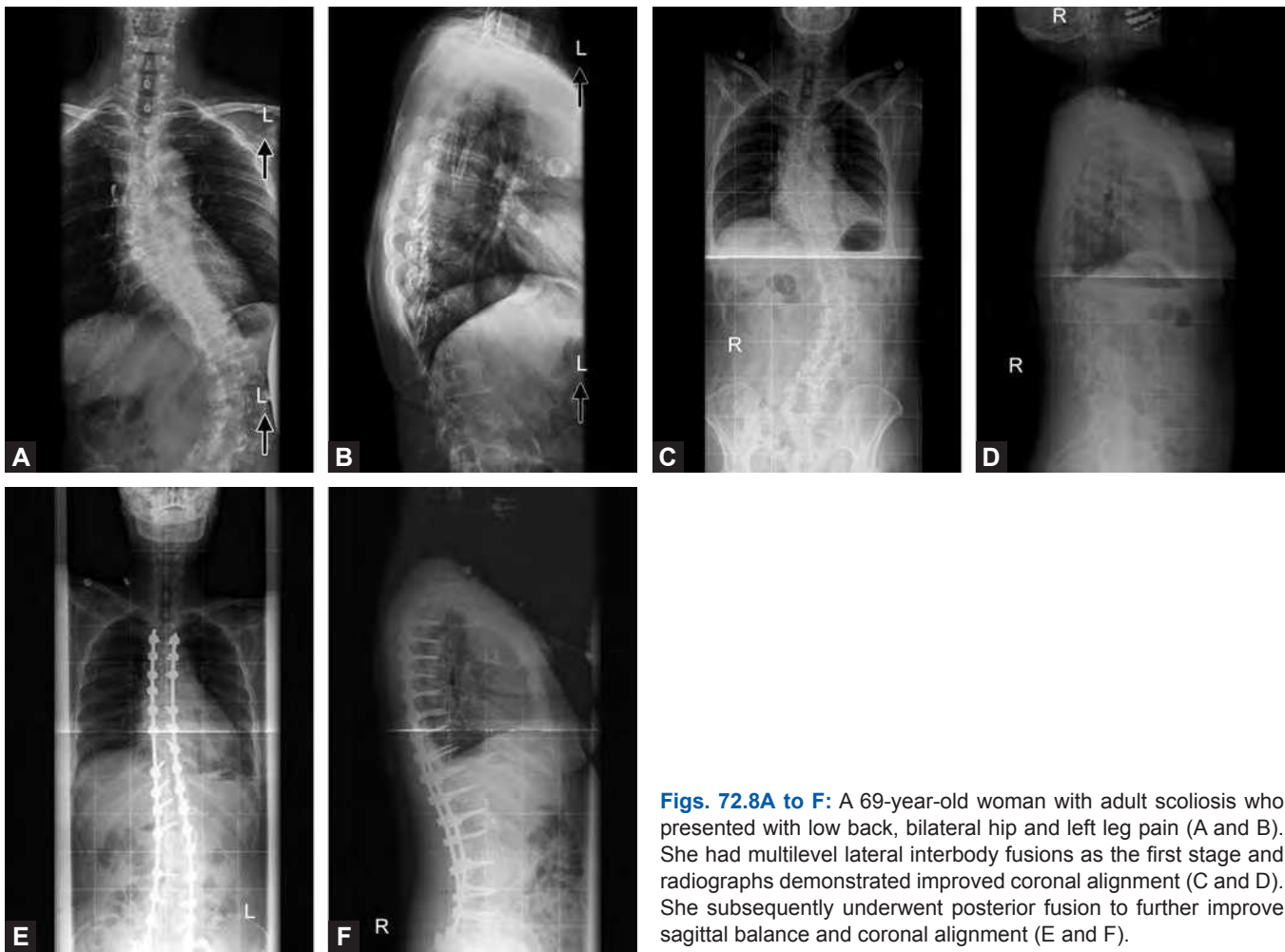


Figs. 72.7A to E: A 79-year-old male presented with degenerative scoliosis (A and B). A CT was performed to evaluate the quality of the endplates, noting sclerosis (C). Stand-alone XLIF was performed at L1-L5 (D and E).

Deciding which side to approach the spine is a critical step in the preoperative planning. Surgical approach from the concavity of the scoliosis is beneficial because it provides access to multiple levels through a single skin incision. The fractional curve at the lumbosacral junction will place the L4-L5 disc in convex side of the fractional curve, but concave side of the main curve. This will provide a reliable approach to L4-L5 where the iliac crest typically can obstruct access from the convex side of the main curve. On the convex side of the curve, the lumbar plexus will already be draped over the curve and under tension. Further traction by the retractors during the procedure would place the lumbar plexus at higher risk for injury. However, on the concave side of the curve, the lumbar plexus will be relaxed; theoretically, the risk of injury to the lumbar plexus will be less. In addition, the soft tissues and bridging osteophytes will be more prominent

on the concave side, and direct release of these structures will allow better curve correction, restoration of foraminal height, and indirect neural decompression.

Despite the advantages of the LLIF technique, there may be scenarios of severe sagittal imbalance where anterior release via LLIF may not sufficiently address the patient's deformity. In such situations, the patient may require aggressive posterior osteotomy techniques; however, even then LLIF would have an adjunctive role to decrease the pseudarthrosis rates by providing interbody fusion. The best example would be while planning a pedicle subtraction osteotomy in a patient with *de novo* scoliosis where there is no previous anterior interbody fusion. Side bending radiographs should be carefully scrutinized for flexibility of the curve. In the presence of a rigid fractional curve, correction of the main curve may lead to coronal decompensation following the LLIF procedure. This



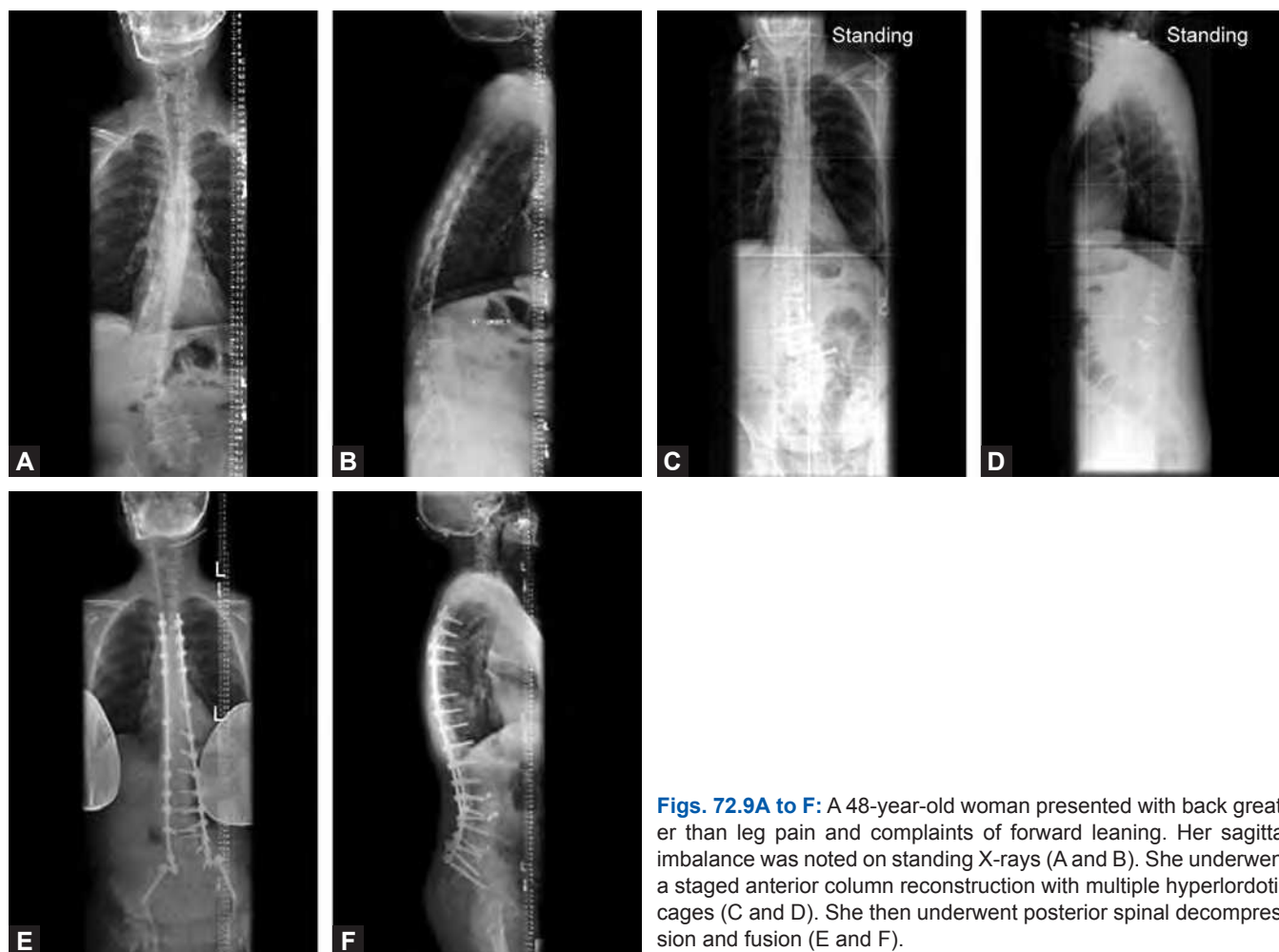
Figs. 72.8A to F: A 69-year-old woman with adult scoliosis who presented with low back, bilateral hip and left leg pain (A and B). She had multilevel lateral interbody fusions as the first stage and radiographs demonstrated improved coronal alignment (C and D). She subsequently underwent posterior fusion to further improve sagittal balance and coronal alignment (E and F).

can be addressed during the posterior procedure; however, awareness of this potential complication is important and should be discussed with the patient before the procedure (Keshavarzi). Finally, it is not uncommon for complex deformity procedures to include L5-S1 as part of the construct. In such cases, the best treatment solution for L5-S1 is often to perform the interbody treatment during supplemental posterior fixation via either ALIF or TLIF.

Case example: A 69-year-old woman presented with low back, bilateral hip, and left leg pain. Pre-operative radiographs showed decompensating away from the convexity of her structural lumbar curve in the coronal plane (Figs. 72.8A and B). After treating the anterior column, the patient experienced immediate reductions in pain and radiographs demonstrated improved coronal alignment (Figs. 72.8C and D). Two days after the anterior portion of the procedure, the

patient underwent posterior fusion to further improve sagittal balance and coronal alignment (Figs. 72.8E and F). One year after the surgery, the patient is able to walk numerous blocks and has increased her lifting abilities to meet her needs for daily living.

5. **Anterior column release to correct severe sagittal plane deformity** (Fig. 72.9): In rigid and acute sagittal plane deformities, a new modification/application of lateral interbody fusion technique is the anterior column release (ACR). This technique involves release of the ALL and anterior annulus in addition to the discectomy. A special interbody cage with up to 30° of lordosis is inserted into the disc space. This technique is frequently combined with a posterior Smith-Petersen osteotomy. Akbarnia et al. reported 28° of correction with the ACR and an additional 7° with posterior osteotomy reaching a total correction of 35°. This is



Figs. 72.9A to F: A 48-year-old woman presented with back greater than leg pain and complaints of forward leaning. Her sagittal imbalance was noted on standing X-rays (A and B). She underwent a staged anterior column reconstruction with multiple hyperlordotic cages (C and D). She then underwent posterior spinal decompression and fusion (E and F).

comparable to the correction achieved with a pedicle subtraction osteotomy, with the advantage of less morbidity to the patient, as the anterior part of the procedure is a separate stage with minimal morbidity. The preliminary results in 17 patients are promising; however, careful case selection is essential. The ideal patient would have an acute kyphotic deformity at the disc level without posterior instrumentation spanning the target segment.

Case example: A 48-year-old woman presents with back greater than leg pain and complaints of forward leaning. Her sagittal imbalance was noted on standing X-rays (Figs. 72.9A and B). She underwent a staged anterior column reconstruction with 100° total of hyperlordotic cages (Figs. 72.9C and D). Two days later, she then underwent posterior spinal fusion with decompression (Figs. 72.9E and F).

CONCLUSION

The use of the LLIF has many applications. It is a useful alternative to the traditional interbody fusion techniques, with expanded indications in standalone constructs and thoracic disc herniation. While there are limitations to its use and inherent risk, with meticulous technique, it is both easily reproducible and safe.

KEY POINTS

- Lateral interbody fusion allows excellent coronal and sagittal plane correction in addition to indirect central and foraminal decompression, making it an important alternative to classic interbody fusion techniques.
- Lateral interbody fusion cages rest on the strongest part of the vertebral endplate decreasing the risk of subsidence significantly.

- Most common complication is neuropraxia; therefore, adherence to meticulous surgical technique and a thorough understanding of the regional neurovascular anatomy is essential.
- A computed tomography scan would be helpful to evaluate endplate sclerosis when considering stand-alone constructs.
- It can be safely utilized in degenerative disc disease and low grade (I&II) spondylolisthesis patients.
- Adjacent segment disease is an excellent indication as it can be performed through a separate approach in a virgin territory.
- Stand-alone constructs should only be utilized in select patients who have advanced facet arthritis, endplate sclerosis and minimal motion on bending X-rays.
- It is a minimal invasive means of achieving coronal and sagittal plane correction in adult spinal deformity patients, and frequently utilized in combination with posterior approaches.
- Anterior Column Realignment is a powerful minimally invasive alternative to pedicle subtraction osteotomy, that allows up to 35° of correction per level. The ideal patient would have a kyphotic deformity at the disc level without a posterior instrumentation spanning the target segment.

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Nonoperative Treatment of Lumbar Disc Herniation

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Snapshot

- » Natural History of Lumbar Disc Herniation
- » Indications for Nonoperative Treatment
- » Outcomes of Nonoperative Treatment
- » Who will Benefit from Nonoperative Treatment?
- » Failure of Nonoperative Treatment
- » Are Some Nonoperative Treatment Methods More Effective than Others?
- » Epidural Injections
- » Targeted Anti-inflammatory Therapies

INTRODUCTION

Radicular pain with or without low back pain is one of the most common musculoskeletal problems encountered by healthcare professionals. In the majority of cases, nonoperative treatment is sufficient for adequate pain control until resolution of symptoms. When the expected benefits of nonoperative and operative treatment are equal, patients tend to prefer the nonoperative approach due to perceived higher risks of surgery.¹ Despite extensive research, many questions still remain on the optimal nonoperative treatment of patients with radicular pain. First, does nonoperative treatment offer any benefits compared with the natural course of the symptom? Second, are some treatment options clearly more effective than others in diminishing pain and improving function in a patient suffering from acute lumbar radiculopathy? Third, are there any inherent risks associated with nonoperative treatment, and for how long should it be continued before deemed as either successful or failed? Finally, is it possible to identify early on those patients who will respond to nonoperative treatment as opposed to those who will eventually need surgery?

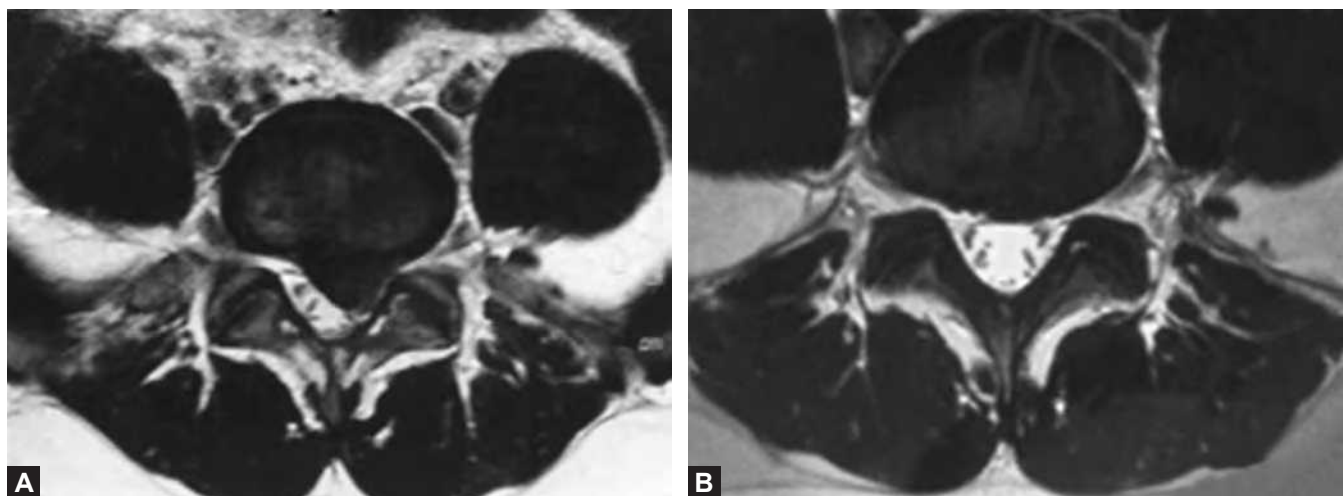
In search of answers to these questions, the following chapter will review the best available evidence on the natural course of radicular symptoms due to a lumbar disc

herniation (LDH), the indications for nonoperative treatment, the effectiveness of nonoperative treatment options, and the possible risks associated with them. This review will be restricted to therapies not violating the confines of the disc space, i.e. any intradiscal techniques are out of the scope of this review.

NATURAL HISTORY OF LUMBAR DISC HERNIATION

Knowledge of the natural history of any clinical condition plays an important role in decisions of whether and how to treat that condition. The treatment should offer clear benefits over the natural course of the disorder without predisposing the patient to unnecessary risks. The natural history of symptoms due to LDH is still inadequately described; in a significant number of patients, the symptoms resolve spontaneously with no formal contact with the health care system, and, thus, without definite diagnosis.

The natural history of an LDH is usually benign, with the majority of patients showing spontaneous resolution of symptoms within a few weeks. Indeed, marked reduction of pain and improvement in function has been shown with no specific treatment in 70% of patients at 4 weeks after the onset of symptoms.² In one prospective observational study with minimal nonoperative intervention, 36%



Figs. 73.1A and B: (A) A left-sided lumbar disc herniation at the presacral level in a 26-year-old woman; (B) One year after the onset of symptoms, the disc herniation has spontaneously reabsorbed. The patient still had residual low back pain radiating to her posterior thighs.

of the patients showed major improvement at 2 weeks, and, after 12 weeks, 73% of patients had experienced at least reasonable improvement.³ However, some evidence suggests that the prognosis of severe sciatica is not as favorable as previously thought, with a significant number of patients still reporting radicular pain at follow-up regardless of the treatment received.^{4,5}

Many LDHs demonstrate a tendency toward natural resorption (Figs. 73.1A and B). The mechanism by which this happens is not fully understood, but macrophage phagocytosis and inflammation are believed to be the most important underlying phenomena. Magnetic resonance imaging (MRI) 12–19 months after the onset of symptoms has shown either a complete resorption or at least a significant reduction in herniation volume in 76–88% of patients.^{6,7} Larger disc herniations, especially sequestered or extruded fragments, seem to have the greatest tendency toward spontaneous resorption over time.^{7–9} Interestingly, no clear correlation between the decrease in disc herniation size and the patient's clinical improvement has been demonstrated.^{8–10}

INDICATIONS FOR NONOPERATIVE TREATMENT

Patients with radicular symptoms and a possible LDH can be treated nonoperatively if they do not show signs of a progressive neurological deficit or cauda equina syndrome.^{11–13} If the patient's radicular pain can be controlled

with nonoperative means, the treatment chosen should interfere as little as possible with the natural resolution of the symptoms.⁶

In clinical practice, patients with radicular pain rarely need imaging of the spine before treatment decisions, and MRI does not have any significant value in planning the initial nonoperative care.¹⁰ Initially, the treatment should be directed at reducing the patient's radicular symptoms, and further diagnostics are reserved for those patients whose signs and symptoms do not resolve with 6 weeks of nonoperative treatment. Magnetic resonance imaging in patients with a 6-week history of radicular symptoms has shown an LDH in two thirds of these patients.¹⁰ Earlier imaging of the spine is indicated if the patient's history or clinical findings suggest a malignancy, infection, or trauma (red flags, Table 73.1), or if the symptoms raise a suspicion of a cauda equina syndrome or progression of a neurological deficit during the observation period.¹⁴ Patients with red-flag findings are usually easily distinguished from those patients with more benign etiology for their radicular pain.

A progressive or significant neurological deficit is generally accepted as a contraindication for nonoperative treatment.^{11–13} Nevertheless, significant recovery of nonprogressive muscle weakness has been reported without surgical intervention. In one prospective observational study, 56% of patients with clinically significant muscle weakness for <1 month were spontaneously improved at 6-month follow-up, and 40% had a complete recovery of their muscle deficit.¹⁵ Bush et al. reported a partial or com-

Table 73.1: Red-flag findings in patients with radicular symptoms indicating a need for advanced imaging of the spine.¹⁴

Findings suggestive of fracture	Significant trauma at any age Minor trauma at older age Age > 70 years Osteoporosis Prolonged use of corticosteroids
Findings suggestive of malignancy	Age < 20 years or > 55 years History of previous malignancy Pain not related to activity General symptoms (weight loss, fever)
Findings suggestive of infection	General symptoms (fever) Pain not related to activity Use of predisposing drugs (corticosteroids, immunosuppressive agents) Use of intravenous drugs
Findings suggestive of cauda equina	Saddle anesthesia Widespread muscle weakness Fecal incontinence Urinary retention or paradoxical incontinence due to overflow
Findings suggestive of failed nonoperative treatment	Progress of neurological deficits Excruciating pain No improvement after 6 weeks of nonoperative treatment

plete recovery of neurological signs in almost all of their patients at 1-year follow-up.⁶ Despite these favorable clinical reports, there is no evidence to suggest that nonoperative treatment would have a positive effect on the natural history of muscle weakness or, indeed, that early surgical treatment would improve the chances of recovery.¹⁶ The clinical course of nonprogressive muscle weakness seems to be of natural resolution in a significant proportion of patients, irrespective of the treatment chosen.¹⁵ Nevertheless, severe muscle weakness for longer than 1 month has been shown to decrease the rate of full recovery after surgical treatment.¹⁷ In conclusion, nonprogressive muscle weakness is not an absolute contraindication for nonoperative treatment, but, in clinical practice, surgical treatment is usually considered if no recovery occurs within 3 months.^{16,17}

There is no consensus on how long nonoperative treatment should be continued before considering surgery in those patients who do not respond to nonoperative means, but do not have an absolute indication for surgery. Furthermore, we do not know whether there is a time window after which permanent damage to the compressed nerve root will cause residual symptoms despite adequate

treatment. Most spine practitioners agree that at least 6–8 weeks should be reserved for nonoperative treatment in the absence of absolute indications for surgery.¹¹ In his classic randomized controlled trial (RCT) comparing nonoperative and operative treatment of LDH, Weber concluded that a minimum 3-month period of nonoperative treatment was necessary to make any decisions on its effectiveness.¹⁸ In another RCT, Peul et al. compared early surgery to 6 months of continued nonoperative care and eventual surgery if needed and concluded that prolonged nonoperative treatment did not increase the risk of unsatisfactory outcome at 2-year follow-up.¹⁹ On the other hand, some recent evidence from the Spine Patient Outcomes Research Trial (SPORT) indicated that although there was no harm in trying nonoperative treatment before surgery, patients with symptoms for >6 months had a better outcome after surgery compared with nonoperative treatment.²⁰ In conclusion, no general rules regarding the duration of nonoperative treatment and the optimal timing for eventual surgery exist, and all decisions must be individualized for every patient.

OUTCOMES OF NONOPERATIVE TREATMENT

Numerous nonoperative treatment options are available for patients with a symptomatic LDH, and many of these have been evaluated under randomized controlled study designs. Yet, the available data are insufficient and at best conflicting, making it difficult to give any evidence-based treatment recommendations.

In an RCT comparing surgical treatment of LDH with nonoperative treatment consisting of mild analgesics and initial bed rest followed by gradual increase of activities, Weber reported that 1 year after the symptom onset, 25% of the nonoperatively treated patients were symptom free and 36% showed satisfactory improvement of their symptoms.¹⁸ In the long-term, up to 10 years of follow-up, the nonoperative group continued to improve with variable recovery patterns. Similar continued improvement with nonoperative treatment was observed in the prospective observational Maine Lumbar Spine Study.^{21–23} With a wide variety of nonoperative treatments, 43% of patients at 1 year after the onset of symptoms, 56% at 5 years, and 61% at 10 years reported their predominant clinical symptom either improved or completely gone. In a more recent prospective study including 340 patients with nonoperative treatment, 41% of the patients reported a successful outcome at 1-year follow-up.²⁴

In summary, significant improvement of symptoms can be expected in 40–60% of patients with different nonoperative treatment strategies. However, there remains a group of patients with substantial symptoms interfering with their daily life after an initial episode of radicular pain. Nykvist et al. reported less favorable long-term results in patients with severe radicular pain at presentation.⁴ At 1-, 5- and 13-year follow-up, 81%, 82%, and 68% of their patients, respectively, suffered from radicular pain regardless of the initial treatment. Further, some evidence suggests that those patients referred to secondary care, either for more severe or continuing symptoms, have a worse prognosis than previously thought; subsequently, 54% and 47% of patients reporting significant radicular pain, and 47% and 39% sustained significant disability at 1 and 2 years after the onset of symptoms, respectively.⁵

Several RCTs have compared the outcomes of operative and nonoperative treatment in well-defined patient populations with LDH.^{19,25–28} A common finding in all these trials has been that although operative treatment seems to result in a faster relief of symptoms, at 1- to 2-year follow-up no significant differences between the treatment groups have been demonstrated. Specifically, Peul et al. noticed a slower and linear recovery in the group receiving prolonged nonoperative care with a median time for recovery of 12 weeks compared with 4 weeks after operative treatment.²⁵ Nevertheless, after 8 weeks no clinically meaningful differences between the treatment groups could be detected, and 79–81% of their patients had satisfactory results whether treated nonoperatively or operatively.¹⁹ Long-term results from the SPORT study report significant and sustained improvement after nonoperative usual care persisting for at least 4 years.²⁷ In conclusion, these RCTs provide conflicting evidence whether operative treatment offers any significant benefit compared with nonoperative treatment for short- or long-term follow-up.²⁹

Results of observational nonrandomized trials have suggested somewhat worse outcomes after nonoperative treatment when compared with operative treatment, especially for the first year after the onset of symptoms.^{18,21,22,24,30} However, this difference seems to diminish with longer follow-up due to continued improvement of the nonoperatively treated patients.

From a societal perspective nonoperative treatment is less costly than surgery, although the difference in costs is balanced, at least short term, by better outcomes among those patients treated operatively.³¹ On the other hand, the gains in quality of life after operative treatment are relatively limited compared with nonoperative care, and

health economic reasons as such do not support early operative treatment in a patient who would prefer nonoperative treatment.³² Moreover, no significant difference in the return to work rates has been noticed between patients treated nonoperatively or operatively.^{22,23,27}

WHO WILL BENEFIT FROM NONOPERATIVE TREATMENT?

Clinical experience and research evidence has demonstrated that many patients with a symptomatic LDH recover with no specific treatment or with minimal intervention, yet others will proceed to surgery due to persisting and intolerable symptoms. Early identification of those patients who respond to nonoperative treatment as opposed to those who will eventually require operative treatment would significantly benefit our spine practices. Some predictors of outcome have been reported in the literature, but the evidence remains inconclusive. Shorter duration of radicular pain at presentation has been identified as a positive predictor regarding success of nonoperative treatment.^{20,24,33} However, in an RCT comparing active “symptom-guided exercises” to sham exercises, patients still improved after months of radicular pain when they received appropriate nonoperative treatment.³⁴ Regarding the prognostic value of the intensity of the radicular pain, or morphology (size and type) of the LDH, a recent systematic review found conflicting evidence.³⁵ Psychosocial factors may be the strongest predictors of outcome,^{5,36} moreover, patients with higher levels of education demonstrated better outcomes after nonoperative treatment than those with lower levels of education.³⁷ Some evidence suggests that even genetic factors affect the individual patient’s response to nonoperative treatment.³⁸

FAILURE OF NONOPERATIVE TREATMENT

Most spine practitioners offer the possibility of operative treatment to those patients who do not respond to nonoperative treatment, although no consensus exists as for how long nonoperative treatment should be continued until it is deemed failed. Variable surgical rates have been reported in groups of patients who initially chose nonoperative treatment for their radicular symptoms. In general, during the first 6–12 months after the onset of symptoms, 2–14% of nonoperatively treated patients opt for eventual surgery.^{4,6,10,21} In the observational cohort of the SPORT

study, 9%, 16%, 22%, and 24% of patients from the nonoperative treatment group decided upon operative treatment by the 3-month, 6-month, 2-year, and 4-year follow-up, respectively.³⁰ Significantly higher failure rates of nonoperative treatment (i.e. surgery rates) have been noticed in a secondary care setting, with 29% of patients at 1 year and 32% at 2 years having undergone surgery for their symptoms.⁵ In all the published RCTs, a significant proportion of patients from the nonoperative treatment arm actually received operative treatment (from 26% to 45% depending on the follow-up time).^{18,19,26,28}

Although the natural course of symptoms due to an LDH is usually benign and self-limiting, many patients experience residual pain and functional limitations after an index episode.^{24,39} In a group of patients with a massive LDH, 85% of the patients reported a satisfactory recovery at 23-month follow-up, but 29% of them still complained of occasional or intermittent low back pain, and 14% suffered from radicular pain.⁸ Significantly higher rates of residual radicular pain, in up to 88% of patients, have been reported from a secondary care setting.⁴⁰ Furthermore, recurrence of radicular pain is relatively common after nonoperative treatment of LDH, with every fourth patient reporting subsequent pain episodes 1 year after resolution of the initial symptoms.³⁹ Recurrence of symptoms was related to a longer time to resolution of the initial pain. Although residual or recurrent radicular pain and functional limitations are possible after nonoperative treatment of LDH, early operative treatment does not seem to diminish the risk of unsatisfactory outcome in the long-term follow-up.^{4,5,19}

Permanent damage to the nerve root or development of a cauda equina syndrome is feared complications of nonoperative treatment. In the randomized cohort of the SPORT study, no patient in the nonoperative usual care group developed a cauda equina syndrome by the 2-year followup,²⁶ and, over 4 years after the onset of symptoms, no evidence of harm from the nonoperative approach could be demonstrated.²⁷ In their RCT comparing early surgery to 6 months of nonoperative care and eventual operation after that period only if needed, Peul et al. could not show that prolonged nonoperative treatment (i.e. delayed surgery) resulted in worse treatment outcomes¹⁹—this might suggest that no permanent damage to the nerve root had occurred. Rather, with the strategy of continued nonoperative treatment, 56% of their patients did not require surgery for satisfactory recovery.

ARE SOME NONOPERATIVE TREATMENT METHODS MORE EFFECTIVE THAN OTHERS?

A wide range of nonoperative treatment strategies are available for the patients with a symptomatic LDH, and many of these have been evaluated in RCTs. However, no standardized treatment protocol exists for these patients. Further, the current evidence on the effectiveness of different treatment options and, indeed, their impact on the prognosis of the clinical symptoms remain limited. The following section will summarize the available evidence regarding the specific interventions frequently applied by spine practitioners and physical therapists for patients with radicular symptoms.

Despite their extensive use for radicular pain, medications have not been widely studied in this patient group. No evidence exists on the effectiveness of nonsteroidal anti-inflammatory drugs (NSAIDs) over placebo.⁴¹⁻⁴³ Due to their anti-inflammatory properties, steroids are sometimes used orally or intramuscularly for pain control. However, oral steroids have not been shown superior to placebo,⁴⁴ and no evidence exists to support the use of intramuscular corticosteroid injections.⁴³ Benzodiazepines should not be used routinely in patients with LDH. In an RCT comparing the efficacy of benzodiazepines with placebo, the probability of significant pain reduction was twice as high in patients treated with placebo compared with patients receiving benzodiazepines.⁴⁵ No evidence supports the effectiveness of opioid analgesics, muscle relaxants, antiepileptic drugs, or tricyclic antidepressants in the treatment of patients with a symptomatic LDH.

Traditionally immobilization has been subscribed to those patients with disabling clinical symptoms. The use of lumbar corsets is not supported by research evidence.⁴¹ Moreover, a systematic review on the effectiveness of nonoperative treatment for radicular symptoms concluded that compared with no treatment, bed rest did not lead to significant improvement in pain or disability.⁴² Specifically, Hofstee et al. compared continuation of daily activities with either physiotherapy or bed rest under randomized controlled study design and noticed that patients receiving either physiotherapy or bed rest did not have a more favorable recovery than patients continuing with their normal daily activities.⁴⁶ Another RCT corroborated that bed rest is not more effective than watchful waiting.⁴⁷

A wide range of physical therapy modalities are being used for patients with radicular symptoms with little evidence supporting their use in general, or any benefit from one treatment strategy compared with others. A recent systematic review suggested that specific stabilization exercise programs would be more effective than watchful waiting in reducing pain at short-term follow-up.⁴¹ Another systematic review found no difference regarding pain and disability at short- or intermediate-term follow-up when comparing physiotherapy with inactive treatment.⁴² Conflicting evidence exists on the effectiveness of physiotherapy compared with other nonoperative care for the overall improvement of the patients, the pain intensity, or working ability at short-term follow-up.⁴² Luijsterburg et al. performed an RCT comparing general practitioner's care (information and advice, pain medication) with physiotherapy in 135 patients with radicular symptoms.⁴⁸ The average patient benefited very little from adding physiotherapy to the general practitioner's care, but for those patients with severe disability the additional physiotherapy seemed to be effective regarding overall improvement. Finally, some evidence suggests that the frequently applied passive techniques to address pain and muscle spasm (e.g. ultrasound and massage) may in fact hinder the patient's recovery.⁴⁹

When comparing manipulation with other nonoperative care, no difference has been reported regarding overall improvement of the symptoms, pain, or return to work at short-term follow-up.^{41,42} In a specific group of patients with an acute LDH and an intact annulus, manipulation was more effective than simulated manipulation for the intensity of radicular pain.⁴¹ However, some concerns remain over the possibility of manipulation exacerbating the symptoms of LDH or causing a cauda equina syndrome. Anecdotal clinical evidence has been published,⁵⁰ although it is often difficult to verify a temporal relationship between the manipulation procedure and the onset of clinical symptoms. Literature suggests that the risk of an iatrogenic cauda equina syndrome with spinal manipulation is as low as 1 in 3.7 million procedures.⁵¹

No significant effect has been demonstrated for mechanical traction in the treatment of patients with a symptomatic LDH.⁴³ Traction was not more effective than sham traction in reducing pain or improving function at short-term follow-up,⁴² and no significant benefit has been demonstrated for traction over other nonoperative treatment methods.^{41,42}

No evidence exists on the effectiveness of acupuncture in the treatment of radicular symptoms due to an LDH.

In summary, very little evidence exists on the above-mentioned treatment methods frequently used for patients with radicular pain, either on the overall effectiveness of those treatments on the patient's symptoms or on the effectiveness of one treatment method over the others. Some frequently used modalities may even be detrimental to the patient's recovery.

■ EPIDURAL INJECTIONS

For decades, ischemia due to mechanical compression of the nerve root was considered the main factor resulting in radicular pain. Our current understanding emphasizes several biochemical inflammatory mediators within the degenerated disc fragments sensitizing the nerve root to the mechanical effects of the disc herniation. In an in vivo animal model, the combination of chronic compression of the nerve root and application of nucleus pulposus material on it caused a more pronounced nerve injury than either alone.⁵² The importance of inflammation in the pathogenesis of radicular pain has led to the use of steroids with or without local anesthetics, administered either into the epidural or transforaminal space, in the treatment of radicular pain. Although the mechanism of action of steroids is not fully understood, they have been associated with anti-inflammatory properties resulting in decreased levels of inflammatory mediators.^{53,54} Interestingly, the anti-inflammatory properties of local anesthetics may even be superior to those of NSAIDs or steroids.⁵⁵

Although a substantial rise in the clinical use of epidural injections has been reported,⁵⁶ their role in the treatment of patients with radicular pain remains controversial. Despite active research, no consensus has been reached on the content and optimal volume of the steroid, the role of local anesthetics, the technical performance of the procedure, or the benefit of repeated injections. Interpreting the published literature is difficult due to differences in type and dosage of steroid used, whether repeated injections were administered or not, heterogeneity of patient populations and outcome variables, and different injection techniques. Due to conflicting evidence on the efficacy of epidural injections in patients with radicular symptoms, some authors do not recommend their use in this patient population.⁴²

Epidural injections have been suggested to those patients who continue to have disabling radicular symptoms despite 6 weeks of appropriate nonoperative treatment,

and in whom the nerve root compression demonstrated by advanced imaging correlates with symptoms and clinical findings.⁵⁷ However, identifying those patients, among the large group of patients with radicular symptoms, who would benefit most from epidural injections remains challenging.⁴⁰ Absolute contraindications for epidural injections include coagulopathy, local or systemic infection, spinal malignancy, or uncontrolled diabetes mellitus.⁵⁸ Allergy to the ingredients of the injectate, congestive heart failure, pregnancy, and a history of steroid psychosis should be regarded as relative contraindications to this intervention.⁵⁸

Epidural injections may contain steroid, and local anesthetic or local anesthetic alone can be administered by caudal, interlaminar, or transforaminal routes. Although the transforaminal route is technically more demanding and requires either fluoroscopic or computer tomography control, it has gained popularity in the recent years. Transforaminal epidural injections are thought to be superior to caudal or interlaminar injections due to a better spread of the injectate into close contact with the actual pathology.^{59,60} Indeed, some RCTs have demonstrated significantly better pain relief with the transforaminal approach than the two more traditional routes of administration.^{61,62}

The overall efficacy of epidural injections in radicular pain has been investigated under randomized controlled study designs with conflicting results. Arden et al. compared the efficacy of three repeated epidural injections with steroid and local anesthetic with sham injections of saline, and noticed that at 3 weeks patients in the epidural injection group had a statistically significant improvement in self-reported function compared with the sham injection group.⁴⁰ However, at 6 weeks the benefit of epidural injections had been lost, and no significant difference in the intensity of leg pain was reported at any of the subsequent follow-up time points. In another RCT comparing epidural injections of steroid and local anesthetic with trigger point injections of saline, 84% of patients in the epidural injection group and 48% in the control group reported improvement in their symptoms with maximal improvement within 6 and 12 weeks, respectively.⁶³ Buttermann randomized patients into either operative treatment or up to three injections of epidural steroids and reported that the degree of improvement in the epidural injection group was similar to that of the surgical group.⁶⁴ Karppinen et al. studied the efficacy of a single nerve root injection in a group of patients with radicular pain randomized to either an injection of steroid and local anesthetic or of saline.⁶⁵ They showed that transforaminal injection with

steroid and local anesthetic was superior to saline injection in terms of pain relief at 2-week follow-up, but not at longer follow-up for up to 1 year. In another RCT comparing injections of steroid and local anesthetic with injections of local anesthetic alone, 54% of patients reported significant pain relief up to 3 months after the treatment.^{66,67}

In vivo animal studies have shown that a combination of steroid and local anesthetic in selective nerve root injections does not result in synergistic actions in preventing pain due to an experimental LDH, thus suggesting that steroids might be unnecessary for selective nerve root injections.⁶⁸ Randomized control trials comparing these two treatment strategies in patients with radicular pain have reported similar findings—no additional benefit from steroids compared with local anesthetic alone.^{69,70} Nevertheless, Riew et al. reported that while selective nerve root injections in general were effective in obviating the need for surgery in surgical candidates with an LDH (Fig. 73.2), those patients who received injections of steroid and local anesthetic were significantly more likely to avoid an operation than patients who received local anesthetic alone.⁷¹

On the other hand, some studies have shown no significant difference in pain relief or disability, either short term or long term, between patients who did or did not receive epidural injections for their radicular pain.^{62,72} In summary, no strong evidence either for or against the efficacy of epidural injections has been published.⁷³ With repeated epidural injections, about half of the patients experience an improvement in their clinical condition.⁷⁴⁻⁷⁶ The possible benefit in patients with an LDH seems to be short term at best.⁴⁰



Fig. 73.2: Selective nerve root injection administered under low-dose computed tomography guidance into the left S1 foramen.

Regardless of the route of administration, epidural injections may give rise to complications due to either technical problems with the injection itself or side effects of the injected steroids. Minor complications have been reported in approximately 10% of patients, with increased pain, facial flushing, and systemic effects of the steroid (elevated blood glucose levels in patients with diabetes, elevated blood pressure, fluid retention, menstrual abnormalities) being the most common.⁷⁷⁻⁸⁰ Dural punctures have been reported in 2-5% of epidural injections; epidural abscesses or hematomas are rare.^{73,81} Although most clinical studies on epidural injections do not report any major complications,^{40,57,59,74,79,80,82} anecdotal case reports of sudden paraplegia immediately after a transforaminal epidural steroid injection have been published.⁸³

In summary, in a subgroup of symptomatic patients with an LDH, epidural injections are effective in relieving pain and improving function. However, the benefit is of short duration, and long-term results probably do not differ from the natural course of the symptom. Although minor side effects are relatively common and usually related to steroid administration, major complications are rarely reported.⁸⁴⁻⁸⁶

TARGETED ANTI-INFLAMMATORY THERAPIES

Biochemical inflammatory mediators originating from the degenerated disc are believed to be important in sensitizing the affected nerve root to the mechanical pressure by the LDH. Animal studies have linked the proinflammatory cytokine tumor necrosis factor alpha (TNF- α) to the nucleus pulposus-induced nerve root injury,^{87,88} suggesting that the injury could be prevented by selective TNF- α inhibition.⁸⁹

Karppinen et al. published promising results from their open-label study treating 10 patients with a symptomatic LDH with intravenous infliximab, a monoclonal antibody against TNF- α .^{90,91} However, in a subsequent RCT comparing intravenous infliximab with intravenous saline, the reduction in radicular pain did not differ significantly between the two groups at any of the follow-up time points up to 1 year.^{92,93} The intravenous saline infusion was remarkably effective in decreasing radicular pain immediately after the intervention, possibly reflecting a powerful placebo effect.⁹² It has been suggested that systemic administration of anti-TNF- α therapy may not be as effective as local administration.⁹⁴ Okoro et al. compared

subcutaneous injections of etanercept, another TNF- α antibody, into the perispinal area to saline injections and concluded that etanercept did not bring any additional benefit over placebo.⁹⁵ Moreover, the third monoclonal antibody against TNF- α , adalimumab, when administered subcutaneously, produced significant differences in pain relief over placebo only during the first 2 days after the treatment.⁹⁶ Finally, when etanercept was administered into the epidural space by the transforaminal route and compared with an identical saline injection, no significant differences in pain relief and disability could be shown between the two groups at 1-month follow-up.⁹⁴

Despite sound theoretical basis and promising preliminary results, the RCTs summarized above do not support the use of anti-TNF- α therapy in patients with a symptomatic LDH. It may well be that several other proinflammatory cytokines besides TNF- α explain the effects of nucleus pulposus on the nerve root.⁹⁷ Indeed, interleukin 1 beta (IL-1 β) and IL-6 have been detected in the paravertebral muscles, annulus fibrosus, and nucleus pulposus of patients with a symptomatic LDH.⁹⁸ A critical time window for an anti-TNF- α therapy may also exist, as the effect of TNF- α seems to be limited to the early stages of the inflammatory cascade.^{93,97} Finally, elevated levels of proinflammatory cytokines (IL-1 β , IL-6, or TNF- α) do not correlate with the intensity of pain,^{98,99} which might at least partly explain the lack of significant pain relief after anti-TNF- α therapy.

In summary, based on best available evidence, TNF- α antibodies should not be used in patients with a symptomatic LDH.

KEY POINTS

- The natural history of LDH-induced radiculopathy is typically a self-limiting process. Rarely is this condition associated with a significant neurological deficit. Natural course of LDH-induced radicular pain is benign and self-limiting in most patients, with larger herniations tending to reabsorb over time.
- Nonoperative treatment of patients with a symptomatic LDH consists of educating the patient on the nature of their condition and the natural course of the symptoms. Treatment should focus on adequate pain control and advice to continue with the normal activities of daily living until the process resolves.
- Numerous nonoperative treatment strategies are available for patients with a symptomatic LDH, but

evidence of their effectiveness remains insufficient. No single intervention is proven superior to the others.

- Currently available nonoperative treatments probably do not affect the natural course of LDH-induced radicular pain, and ideally the treatment should interfere with the natural course of the symptom as little as possible.
- Patients undergoing surgery for LDH-induced radiculopathy have a more rapid resolution of their symptoms when compared with their nonoperative counterparts but at 1- and 2-year follow-up no significant difference between operatively and nonoperatively treated patients has been shown.

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Open Operative Treatment of Lumbar Disc Herniations

Luca Papavero

Snapshot

- » Surgical Techniques
- » Postoperative Care
- » Complications
- » Critical Evaluation

“As you leave the OR after an apparently successful microdiscectomy, remember that a successful surgical outcome depends 90% on patient selection and only 10% on technique.”

—John A McCulloch¹

INTRODUCTION

Microsurgical versus Nonmicrosurgical Techniques

The spectrum of open surgical treatment of lumbar disc herniations (DH) ranges from conventional technique without optical magnification, to the use of surgical loupes or microscopy. Although there is a still ongoing debate about the benefits of the use of microscopy for discectomy for the medium and long-term outcome, the short-term advantages include less damage to the paravertebral muscles, decreased blood loss, and reduced postoperative morbidity. These benefits far outweigh the relative disadvantages such as the learning curve.²⁻⁵ In our experience, once this hurdle has been overcome, there is no reason to operate without the aid of a microscope. The surgical techniques described in this chapter are best performed with the aid of the microscope, although they are feasible also with loupes.

Fragmentectomy versus Discectomy

When symptoms are caused by an extruded disc fragment, the disc space should not be cleared. The removal of disc

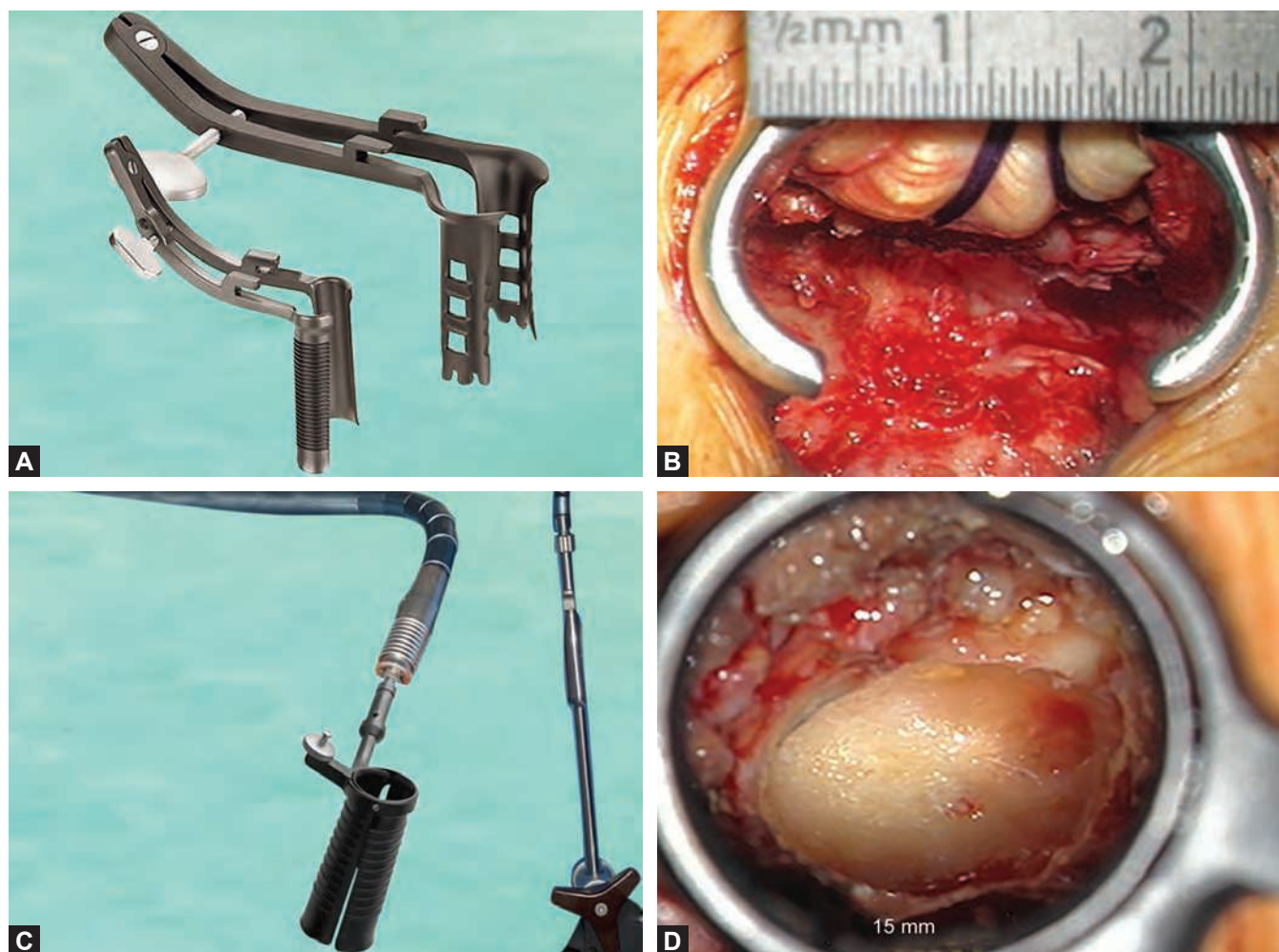
material from the disc space does not lower the recurrence rate for an extruded fragment, but may increase the post-surgical back pain due to segmental instability.^{6,7}

Subperiosteal versus Transmuscular Approach

The subperiosteal (SP) approach requires the incision or retraction of the ligamentous insertions of the paravertebral muscles from the spinous processes. The iatrogenic intraoperative injury of the posterior supporting structures of the lumbar spine may lead to increased postoperative back pain.⁸⁻¹⁰

The microendoscopic discectomy (MED) technique was introduced by Foley and Smith.¹¹ It was the first technique that addressed the shortcomings of the conventional SP approach. Many investigators have reported that MED is associated with less postoperative pain, a shorter hospital stay, and more rapid return to work.¹²⁻¹⁴ However, MED has some limitations related to a smaller operative field, visualized through a cylindrical tubular retractor.¹⁵

The paraspinal muscle-splitting or “Wiltse” approach along the natural cleavage planes of the paraspinal muscles has shown to cause less damage and retraction



Figs. 74.1A to D: (A) Modified minimally invasive speculum-retractor versus conventional; (B) In site; (C) Expandable tubular retractor with a holding arm; (D) In site.

of the paraspinal muscles compared to the SP approach.¹⁶ This leads to decreased back pain and less postoperative analgesic consumption during the early postoperative period.¹⁰ The choice of the transmuscular (TM) approach may be left to the surgeon's preference in patients with fatty degenerated muscles, and it is recommended whenever minimizing muscle traumatization becomes an issue.

Retractors: Miniaturized (Tubular) versus Conventional

The introduction of TM approaches via tubular or miniaturized speculum-retractors has prompted the development of miniaturized surgical tools, which are sized between the conventional microsurgical instruments and the endoscopic ones. Their design facilitates the

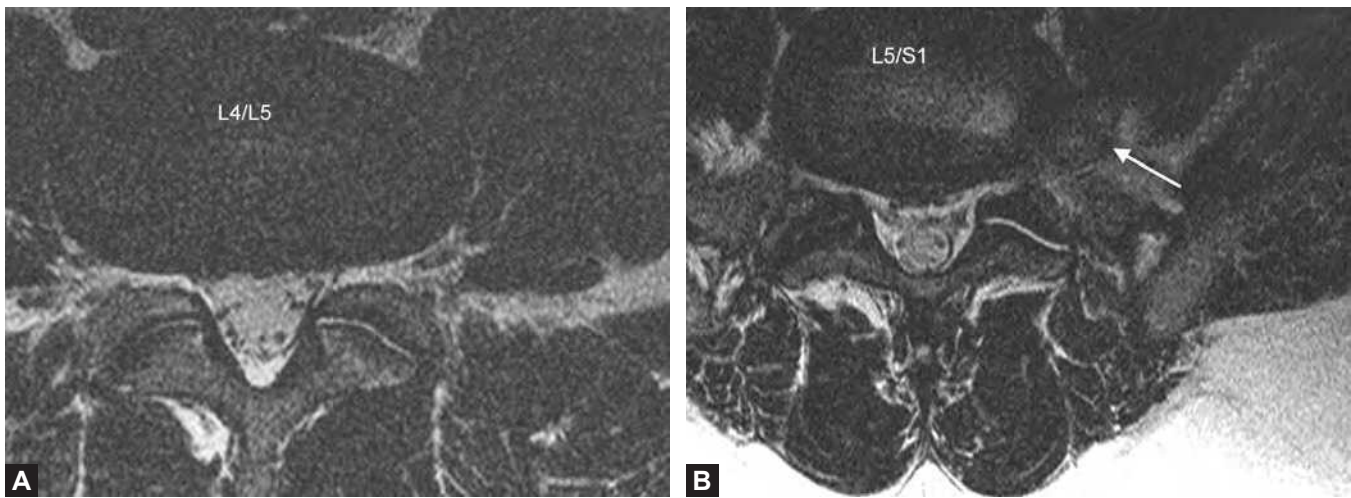
intraoperative view of the surgical target area (Figs. 74.1A to D). Surgical times are comparable to open conventional techniques.

SURGICAL TECHNIQUES

Primary Disc Herniations

Interlaminar Approach^{17,18}

- Indications
 - All contained or extruded disc fragments between the midline and the medial border of the pedicle. In relation to the disc space, the fragments may be caudally or cranially extruded. In the latter case, the translaminar approach is preferred.

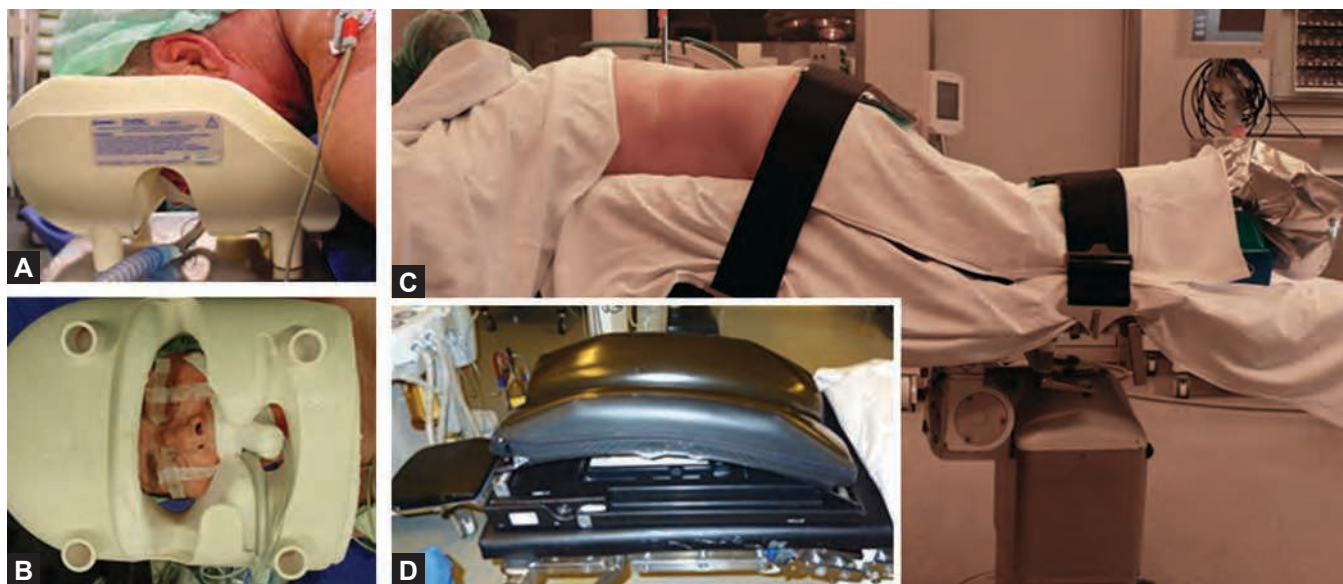


Figs. 74.2A and B: Clinical teaching case: A 42-year-old gentleman presented with mild low back pain and severe left-sided L5 pain requiring opioids for 3 weeks. The examination demonstrated a left-sided foot dorsiflexion weakness. (A) Because the axial magnetic resonance imaging—slice L4/L5 was reported as normal, no further therapy was proposed; (B) A large extraforaminal DH L5/S1 (arrow) was overlooked. Complete remission of symptoms after surgical removal of the disc fragment.

- Disc herniation combined with central/lateral recess stenosis or with asymptomatic segmental instability
- Recurrent DH
- Contraindications
 - Foraminal or far lateral DH, which are located lateral to the lateral border of the pedicle.
- Preoperative planning
 - *Biplanar plain radiographs:* Optional in primary cases, provided that the magnetic resonance imaging (MRI) investigation encloses a coronal slice (scoliosis). Mandatory in: (1) recurrent DH cases to evaluate bony defects; (2) whenever the MRI leads to suspicion of a bony abnormality (spina bifida, pars interarticularis defects).
 - *Magnetic resonance imaging sagittal slices:* Contained DH or extruded fragment? Caudal or cranial (suitable for translaminar approach) fragment dislocation? Mid-vertebral body herniation (half-way between two disc spaces)? *Foraminal slice:* Black neuroforamen? *Extraforaminal slice:* Disc fragment still apparent? *Axial slices:* Axillary disc fragment? How much of the DH is underneath the thecal sac, intraforaminal or extraforaminal (Figs. 74.2A and B)? Pseudomeningocele in recurrent disc surgery? *Coronal slices:* Which approach for combined intraforaminal and extraforaminal DH? *Gadolinium-enhanced slices:* Amount of scar tissue on the way to and into the spinal canal? Differentiation between recurrent DH and scar tissue?
 - *Computed tomography (CT) scan:* Secondary choice whenever MRI contraindicated or not available. *Disko-CT* (= discography + CT): Helpful in suspected extraforaminal DH. *Contrast medium-enhanced CT:* indicated for recurrent disc, differentiation between intraforaminal DH and neurinoma.
- Positioning

We recognize that several positions could provide good clinical results, especially with experienced operating room personnel. The details of our preferred positioning technique are described below:

 - The patient is placed prone on the Wilson frame. Advantages: Hip and knee joints are only moderately flexed, especially important in obese patients! The lordosis of the lumbar spine should be reduced as required by increasing the height of the arches. The distance between the arches can be adjusted according to the size of the patient in order to allow a free hanging abdomen to reduce bleeding (Figs. 74.3A to D).
 - The head is positioned into a Prone View mask (Manufacturer: Dupaco, Oceanside, CA). Eyes, nose, and chin are protected: the anesthesiologist is able to check them intraoperatively by the use of a mirror (Figs. 74.3A to D).
 - For safety reasons, the patient is secured with a belt on the gluteal area: this becomes helpful when the operating room (OR) table has to be tilted away



Figs. 74.3A to D: Positioning for open lumbar disc surgery: (A) The face is embedded in an anatomically tailored foam; (B) The mirror enables a continuous monitoring of the eyes and of the tube; (C) The lumbar spine is parallel to the floor. The belts secure the patient during tilting the table 30° away from the surgeon, as required in extraforaminal disc surgery; (D) The Wilson frame can be adjusted according to the size of the patient and may open up the interlaminar window by decreasing the lumbar lordosis.

from the surgeon, e.g. in dealing with extraforaminal or far lateral disc herniations (EFDH).

- The OR table is tilted until the lumbar spine is parallel to the floor.
- *X-ray localization:* A 2-cm skin incision does not allow a “seek and find” surgery. Therefore, the correct X-ray localization of the surgical target area is of paramount importance. The needle is always inserted contralateral to the intended surgical side in order to avoid subcutaneous or intramuscular hematoma, and off the midline in order to prevent inadvertent cerebrospinal fluid (CSF) leakage. The needle is perpendicular to the target area (and to the floor): soft-tissue dissection is easier straightforward down. Even small oblique deviations can lead to the wrong level, especially in obese patients. The needle should point to the equator of the target disc. With increasing experience, the surgical field may be narrowed further to only the extruded disc fragment.
- **Soft-tissue approach**
The interlaminar space can be approached via a SP or a transmuscular/paramedian (TM) route. Although the use of the microscope “from skin to skin” is optional, its advantages will be appreciated in dealing with a miniaturized surgical corridor. The most relevant steps are described here:
 - Prophylactic antibiotic coverage (e.g. cefazolin or cephazolin) 30 minutes before the skin incision.
 - *Skin:* 2 cm incision, 5 mm (SP) or 10 mm (TM) off the midline.
 - *Fascia:* (SP) Slightly semicircular incision toward the midline. Five holding sutures on the medial lip secured to a clamp with weights. (TM) Straight incision with one holding suture on each side.
 - *Muscle:* (SP) Paramedian retraction of the paravertebral muscles from the interspinous ligament. Sharp dissection of the rotators from the lower rim of the superior lamina and from the facet joint capsule. Insertion of a miniaturized speculum-counter-retractor system (Figs. 74.1A and B; manufacturer: Medicon, Tuttlingen, Germany).
 - (TM) Blunt splitting with the index finger until the laminofacet junction can be palpated. Opening of the muscular corridor with miniaturized muscle retractors or with a dilator. Insertion of an expandable tubular retractor (Figs. 74.1C and D; manufacturer: Medicon, Tuttlingen, Germany) to 15 mm or 18 mm diameter. Both the speculum and the tube may be secured to the OR table with a self-holding arm or the “snake” (Figs. 74.1C and D).
 - *Interlaminar space:* From this step onward, the surgical technique is identical. The lower rim of

the cranial lamina, the medial border of the facet joint, and the yellow ligament are the areas of interest. Radiographic confirmation of the level is performed. Following a lateral flavectomy or flavotomy with suspension sutures, the epidural fat is exposed. The medial border of the inferior articular process is undercut or drilled off until the shoulder of the root is palpated.

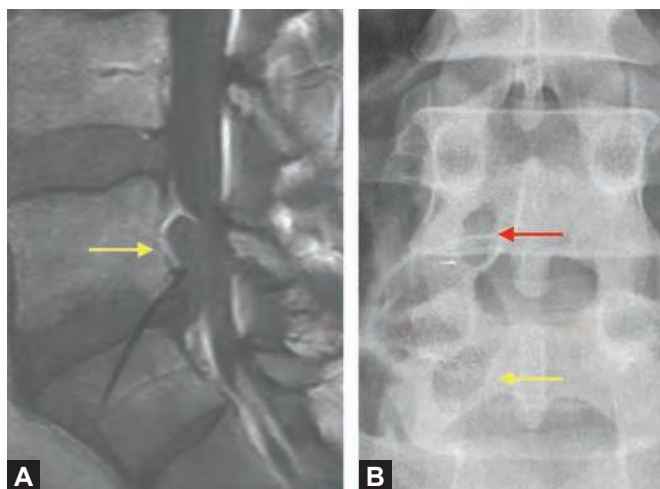
- *Epidural dissection:* Cranial and caudal dissection of the epidural fat performed with a microdissector and a flat sucker along with careful bipolar coagulation of veins, which opens access to the root-DH complex.
- Exposure of the herniated disc
 - *Management of the DH:* The local anatomy will dictate the necessary steps. Usually, a gentle dissection between root and disc material is accomplished first. In our experience, the root retraction is performed intermittently with a flat sucker instead of with a conventional root retractor. Free disc fragments are removed with miniaturized forceps (Manufacturer: Medicon, Tuttlingen, Germany). If indicated, the annulus is split bluntly with the dissector or with a scalpel and further disc material is removed. In the authors' experience, additional discectomy is performed in 20–30% of the cases.
- Closure
 - The disc space, when opened, is rinsed with normal saline. The opening of the annulus is closed with a collagen sponge coated with fibrinogen and thrombin (Tachosil, Manufacturer: <http://www.Takeda.co.uk>). The epidural fat is mobilized in order to cover the root. Careful hemostasis goes along with closure by layers.

Translaminar Approach¹⁹⁻²³

- Indications
 - Cranially extruded disc fragments pushing the exiting root against the lower rim of the pedicle. Usually they are located within the root canal between two lines marking the medial and lateral border of the superior facet.
 - Recurrent cranially extruded disc fragments of DH previously removed via an interlaminar approach.
- Contraindication
 - Lack of an adequate bony lamina, e.g. severe spinal canal stenosis and spina bifida.
- Preoperative planning
 - *Magnetic resonance imaging (sagittal slices):* Measure the distance between the upper border of the disc

space and the lower rim of the cephalad pedicle. The translaminar hole will be centered on the halfway of this distance. *Axial slices:* Look at how much of the bulk of the DH is underneath the thecal sac and how much is lateral of it or even intraforaminal. The translaminar hole is centered on the lateral border of the dura.

- Positioning
 - Basically the same as for the interlaminar approach
 - *Important:* The target lamina should be parallel to the floor. This may require the surgeon to tilt the OR table in a reverse Trendelenburg position. The advantages of a horizontal target lamina are two-fold: the placement of the retractor blade and the drilling of the hole becomes easier (Figs. 74.6 and 74.7A to D).
 - Radiographic localization: The needle should point to the largest portion of the DH, which is usually halfway between the upper border of the target disc and the lower rim of the cranial pedicle. At the beginning of the learning curve, these landmarks may be labeled on the skin incision.
- Soft-tissue approach
 - The lamina can be approached via a SP or a TM route. The soft-tissue approach mirrors the interlaminar approach. Remember: The width and the overlapping of the lamina in relation to the disc space increase in the caudal-cranial direction, whereas the width of the isthmus decreases. This means that the translaminar hole will be more medially and oval-shaped in the upper lumbar levels (Figs. 74.4A and B).
 - *Lamina:* Irrespective of the type of retractor used, the lateral border of the lamina should be visible underneath the retractor valve. A dissector is placed onto the lamina where the bulk of the DH is suspected and a fluoroscopic localization is performed (Fig. 74.5). At this point, the lamina should have been tilted parallel to the floor, so that the high-speed cutting burr can be held easily perpendicular to the lamina. With slow circular movements, a round (L5) or oval-shaped (L4 and cranially) hole of about 10 mm in diameter is performed (Figs. 74.6 and 74.7A to D). Three layers “white” (outer cortical bone), “red” (spongy bone), and “white” (inner cortical bone) will be drilled off. For the sake of safety, the inner cortical bone should be drilled with a diamond burr. Remarks: (1) At least



Figs. 74.4A and B: Clinical teaching case: (A) The cranially extruded L5/S1 disc fragment (yellow arrow) is a good indication for the translaminal approach; (B) Unfortunately, the surgeon omitted the intraoperative fluoroscopic control after having approached the lamina because he “felt” that it was the right level. The translaminal hole L4 (red arrow) did not show any disc fragment. Following the fluoroscopic check, a new hole was drilled at the L5 level (yellow arrow) and a large disc fragment was removed. Fortunately, the translaminal approach spares the corresponding facet joint. Nevertheless, the intraoperative X-ray confirmation of the correct level before drilling off the bone is a must!

3 mm of the lateral border should be spared in order to avoid a fracture of the pars interarticularis (Fig. 74.6). (2) Usually, the translaminal hole is located just cephalad to the cranial insertion of the yellow ligament. So, after removal of the thin shell of inner cortical bone with small patches, epidural fat will appear.

- *Epidural dissection:* Up and down dissection of the fat along the lateral border of the dura. That should be continued cranial up to the axilla of the exiting root.
- Exposure of the herniated disc
Usually an extruded or subligamentous disc fragment/s can be mobilized. After decompression, the root slips caudally into the visible field (Figs. 74.7A to D). The foramen is then probed with a double-angled hook or blunt probe. If an extensive annular perforation is detected, the disc space should be cleared. In our experience that was required in merely 20% of the cases. The rate of recurrent DH was 7%.
- Closure
 - Gelfoam soaked with a long-acting steroid to fill in the hole is optional, but should be avoided if the disc space has been cleared.

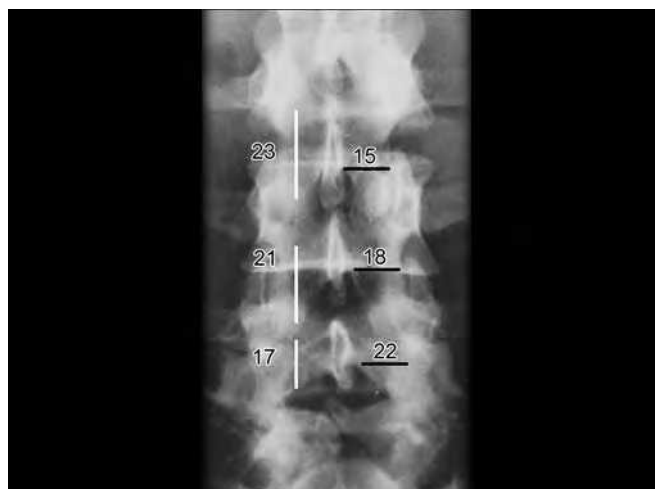


Fig. 74.5: The up-down length of the lamina (white figures) increases, whereas the width of the isthmus (black figures in mm) decreases in the caudal-cranial direction. That means the overlap of the disc by the lamina increases also in the upper lumbar levels. Furthermore, there the translaminal hole becomes more paramedian and oval-shaped.

Extraforaminal or Far Lateral Approach²⁴⁻²⁶

- Indication
 - Disc herniation whose bulk is located at least two-thirds lateral to the pedicle
- Contraindication
 - Foraminal DH located more than two-thirds inside the root canal
- Preoperative planning
 - *Magnetic resonance imaging sagittal slices:* Usually scans are not lateral enough, i.e. lateral to the root canal, and may miss the extraforaminal disc herniation (EFDH). *Axial slices:* compare the amount and distribution of the extraforaminal fat tissue on both sites. *Coronal slices:* although rarely performed, they are of invaluable assistance to show the spatial relationship between exiting root, root canal, and the extraforaminal compartment.
- Positioning
 - Basically the same as for the interlaminar approach
 - For safety reasons, the patient should be belted on the gluteal region: the OR table has to be tilted 20–30° away from the surgeon in order to get a better oblique view of the extraforaminal compartment. Morbidly obese patients may risk “roll over” on to their abdomen.
 - Radiographic localization: Lateral view: Insert a spinal needle one finger’s breadth lateral to the spinous process, perpendicular to the skin and

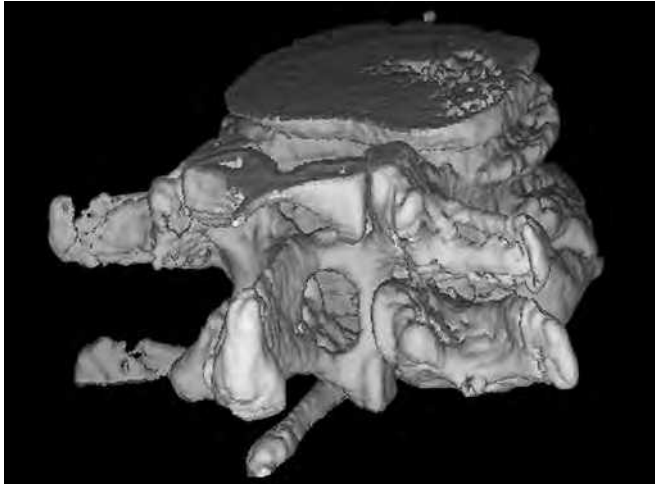
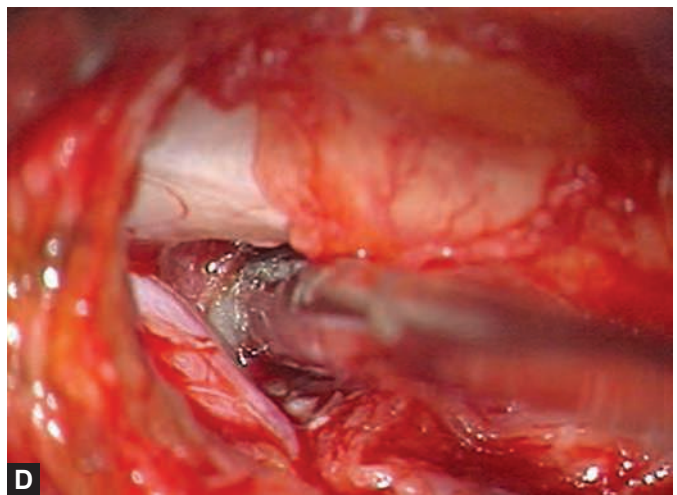
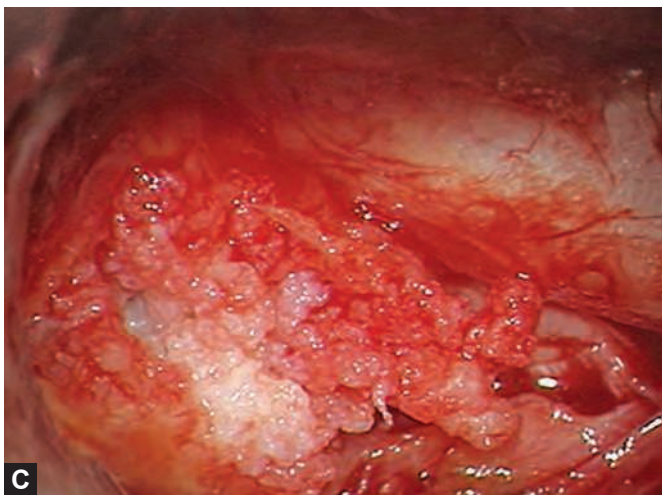
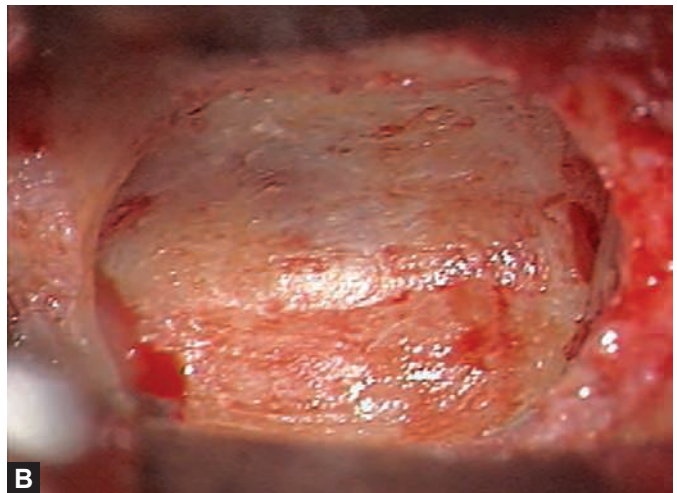
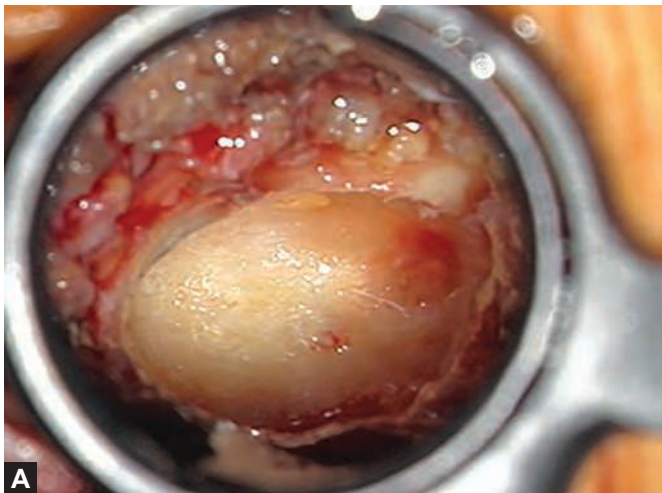


Fig. 74.6: The three-dimensional computed tomography shows a translamellar hole at L3. *Note:* The facet joint L3/L4 is intact and a sufficient lateral rim (5 mm) of the pars is maintained where the bone is the strongest.



Figs. 74.7A to D: (A) A left-sided 10 mm translamellar hole at L4 with an intact inner cortical bone is seen through the expandable tubular retractor (15 mm Ø); (B) Close-up view showing the lateral part of the dural sac and epidural fat tissue bordering it; (C) Following dissection of the epidural fat, a large extruded disc fragment appears in the axilla of the exiting L4 nerve root; (D) After the removal of the disc fragments, the L4 nerve root slips back into the visible field.

projecting toward the lower border of the affected disc space. Draw a horizontal line at this level (A).

- Anteroposterior view: Two horizontal lines are drawn: (1) The lower border of the affected disc (A); (2) The lower border of the transverse process above the affected disc (B). Two vertical lines are also drawn: (1) The midline [row of the spinous processes] (C); (2) a line about 4 cm off to the midline, marking the lateral boundary of the pedicle above and below the affected disc (D). The distance between the two horizontal lines (AB) is the skin incision and will be 3–4 cm in length and about 4 cm paramedian (Figs. 74.8A to E).

- **Soft-tissue approach**

The paraspinous TM blunt-splitting approach to EFDH at the level L4/L5 or more cranially can be performed with an expandable tubular retractor or with a miniaturized speculum combined with medial and lateral counter-retractor blades. At the level L5/S1, the author recommends the use of two counter-retractors inserted perpendicular to each other. That allows to choose four blades of different lengths matching with the following structures: facet joint (medial), transverse plane (lateral), transverse process (cranial), and ala (caudal) (Figs. 74.9A and B). Furthermore, the use of the microscope “from skin to skin” is advised.

- *Skin*: 3 cm in length 4 cm off the midline.
- *Transmuscular route*: After incision of the fascia of *Musculus erector spinae*, the muscle is dissected bluntly using the index finger along the cleavage plane between the multifidus and the longissimus muscle (Figs. 74.8A to E). If this intermuscular plane cannot be palpated, the muscle is split downward to the medial third of the transverse processes. The selected retractor is then introduced so that the tips rest firmly on the lower half of the upper transverse process and on the upper half of the lower one. The lateral surface of the pars interarticularis represents the medial border of the surgical exposure. Fluoroscopic confirmation at this point of the procedure is essential (Figs. 74.8A to E).
- *Extraforaminal approach*: Tilting the OR table by 20–30° away from the surgeon gives a better view of the area lateral to the pedicle. Drilling off bone is usually not necessary, except in the case of an extremely hypertrophied facet joint or at the L5/S1 level. The medial half of the intertransverse muscle is incised and pushed laterally, thereby exposing the intertransverse membrane, also called the

intertransverse ligament. Use of bipolar cautery is essential to maintain hemostasis and a blood-free surgical field. After incision of the membrane, the fat surrounding the nerve appears. Because of the proximity of the nerve, the accompanying vessels, and DH, the sucker should also be used as a nerve retractor. However, beware of an excessive retraction of the dorsal root ganglion in order to minimize the incidence of postoperative burning dysesthesias, which should be counseled to the patient preoperatively. Branches of the radicular artery should be dissected carefully and spared whenever possible. The accompanying veins can be cauterized, if they hinder the access to the disc fragment.

- **Exposure of the herniated disc**

Management of the DH: Typically, we find the nerve and the ganglion pushed laterally and cranially by the free disc fragment. Usually, removal of the fragment alone is sufficient. If an extensive perforation of the annulus is evident, clearing of the disc space should be considered. After probing the root canal with a double-angled blunt hook for residual fragments, the nerve may be covered with a gelfoam soaked with crystalline steroid.

- **Closure**

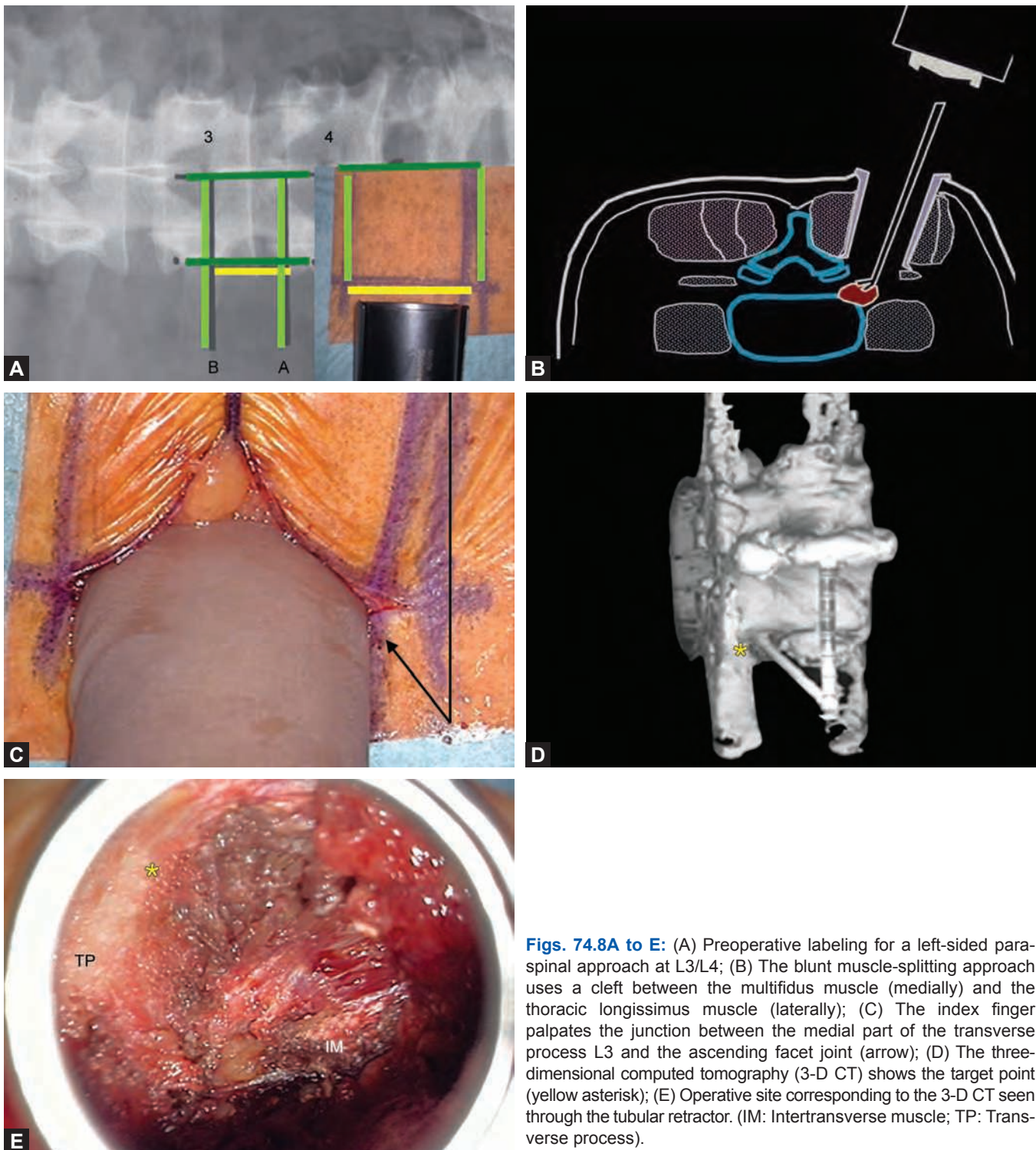
- Placing a drain is optional and in our experience seldom necessary. Muscles do not require suturing.
- *Special considerations for the L5/S1 level*: Because of the particular anatomic relationship between disc space, transverse process L5, and ala, the microsurgical muscle-splitting approach at the lumbo-sacral level should be practiced by a surgeon who is already familiar with the technique at the more cranial levels. Repeated intraoperative fluoroscopic checks may also be necessary. If difficulties arise, switching to the conventional macroapproach should be considered.

Recurrent Disc Herniation^{27,28}

A prevalence of 7–10% recurrent herniations is reported in the literature independently of the surgical technique used. To deal with a recurrent DH usually does not mean to perform a “re-do surgery” identical to the first procedure. The peculiarities of surgery for recurrent DH will be addressed.

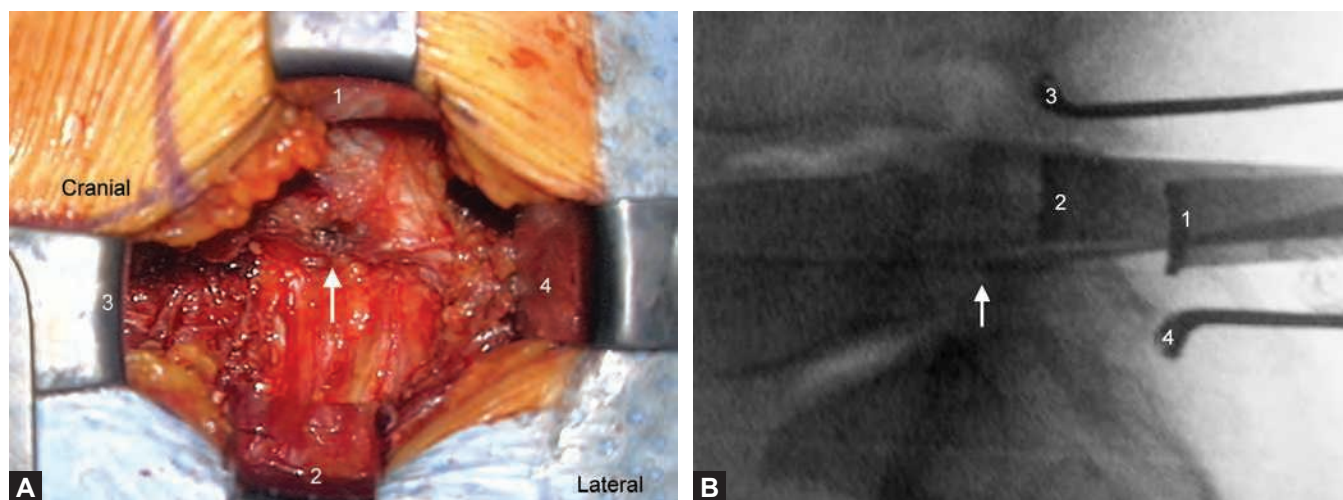
- **Preoperative planning**

- The use of the microscope in our view is a must as it facilitates the differentiation between scar tissue and the dural sac.



- Bypassing most of the scar tissue is imperative. This can be achieved either by using a wider approach than the first one exposing the lower edge of the

upper lamina or the medial wall of the pedicle where unscarred dura can be found. The translaminar approach of a recurrent cranially extruded disc



Figs. 74.9A and B: (A) Operative site of a left-sided paraspinous approach L5/S1: Four slim retractor blades of different lengths are inserted. (1) Ascending facet (medial); (2) Thoracic longissimus muscle (lateral); (3) Transverse process L5 (cranial); (4) Ala sacri (caudal); the white arrow shows the point where the nerve L5 is to be expected; (B) Intraoperative fluoroscopic check: the dissector points to the target point (white arrow).

fragment can be used via a virgin translaminar route instead of dissecting the interlaminar scar tissue.

- Preoperative radiographs show the amount of previously resected bone. This is of paramount importance if previous surgery has been performed elsewhere. If doubts persist, the CT scan provides useful information about the bony landmarks that will guide the surgical approach.
- Gadolinium-enhanced MRI shows the relationship between scar tissue and true recurrent disc material and may differentiate the two. However, this holds true if the recurrent DH occurs roughly within 3 years after the first surgery. Furthermore, endplate Modic lesions and CSF collections should also be closely examined.
- Positioning
 - The same as performing virgin surgery.
- Soft-tissue approach
 - Fluoroscopic labeling of the target area is mandatory as the scar of the skin may slip depending on the positioning and on the amount of subcutaneous tissue.
 - Cautious sharp SP dissection is recommended to the interlaminar window. The lower border of the cranial lamina, the medial border of the remnant facet joint, and the upper border of the caudal lamina should be clearly visible.
 - The most commonly used entry point is the area between the cranial border of the epidural scar and the virgin dura. If this approach should fail, the area between the medial border of the pedicle and the shoulder of the traversing root is an alternative option.
- Exposure of the herniated disc
 - A generous decompression of the root in the lateral recess should precede the mobilization of the nerve from the annulus or from the extruded disc fragment. An intraoperative single shot steroid may be helpful at this stage of the procedure by the anesthesiologist.
 - “Peeling” of the fibrous tissue from the nerve carries a high risk of injuring the dura and does not provide a better clinical outcome. Before biting with the Kerrison punch, a light tug may show movement of scarred dura jump: a sentinel sign of an imminent dural tear.
 - The disc space can be entered laterally from the border of the dural sac and cleared. This reduces the pressure on the extruded disc material. Repeated flushing with saline within the disc space may bring further disc material to the surface. We do not recommend curettage of the endplates. The fibrous pocket containing the extruded disc material is opened and its content removed bluntly with straight/angled probes of different length. A tiny fibrous shell is left adherent to the dural sac. There is no evidence that forced “neurolysis” provides a better clinical outcome.

POSTOPERATIVE CARE²⁹

- *Uncomplicated surgery:* The patient is encouraged to leave the bed 6 hours after surgery. Sitting is allowed starting from the first postoperative day. Physiotherapy starts the morning after surgery. Hospital stay is usually 1–3 days.
- *Standard dural repair:* 48 hours of bed rest with the head in slightly Trendelenburg position (head down). If intraoperative loss of CSF was significant, the patient is treated with intravenous hydration + promethazine + analgesic regimen.
- *Very difficult dural repair not watertight at the time of wound closure:* Closed subarachnoid drainage obtained by puncture at one level above the dural opening and the catheter placed at the thoracic-lumbar junction. The amount of CSF can be controlled by the level of the collection bag relative to the lumbar spine. Cerebrospinal fluid drainage can be continued up to 1 week and should cause mild headache.

COMPLICATIONS

The literature lists several “generic” complications such as deep vein thrombosis, pulmonary embolism, and urinary infections that are fortunately rare. Retroperitoneal major vessel injuries and postoperative visual disturbances (risk factors: diabetes mellitus, long operation time) are even more rare.

Microsurgical discectomies have significantly less severe intraoperative complications as compared to non-microsurgical discectomies.³⁰ Experienced surgeons have significantly less complications (2.2%) than beginners (10.7%).³¹ Recurrent surgeries are burdened with a higher incidence of complications.³²

The most common complications of even refined microsurgical techniques are wrong level surgery, dural opening/CSF leakage (2–7%), root injury (0.06 %), and spondylodiscitis (0.4–1%).

Some remarks about the first two pitfalls:

- *Wrong level surgery*
 - The surgical target area should be as much parallel to the floor as possible.
 - Use a spinal needle (for CSF tap: more expensive, but also more radiopaque, especially in adipose patients) perpendicular to the back, one finger’s breadth off the midline, down to the lamina, contralateral to the intended surgical approach, and pointing to the upper rim of the disc space.

- Label the corresponding horizontal line, the midline, and the skin incision.
- Drape the C-arm (lateral view) and park it conveniently in the surgical suite.
- Time out procedure: confirm the correct level and side of surgery.
- Repeat the trajectory of the cannula inserting the retractor. Remember: in overweight patients, a minimally oblique trajectory can lead a surgeon to the wrong level.
- *C-arm:* Check the level before drilling off bone.
- Do not rely on scars in recurrent surgery; mark the skin incision with the aid of radiographic localization.
- The intraoperative threshold for obtaining a fluoroscopic confirmation should be low.

Dural opening

Each dural opening requires a specific treatment depending on location, shape, and size of the lesion, potential concomitant injury of the cauda fibers, microsurgical skills of the surgeon—just to mention the most important factors.

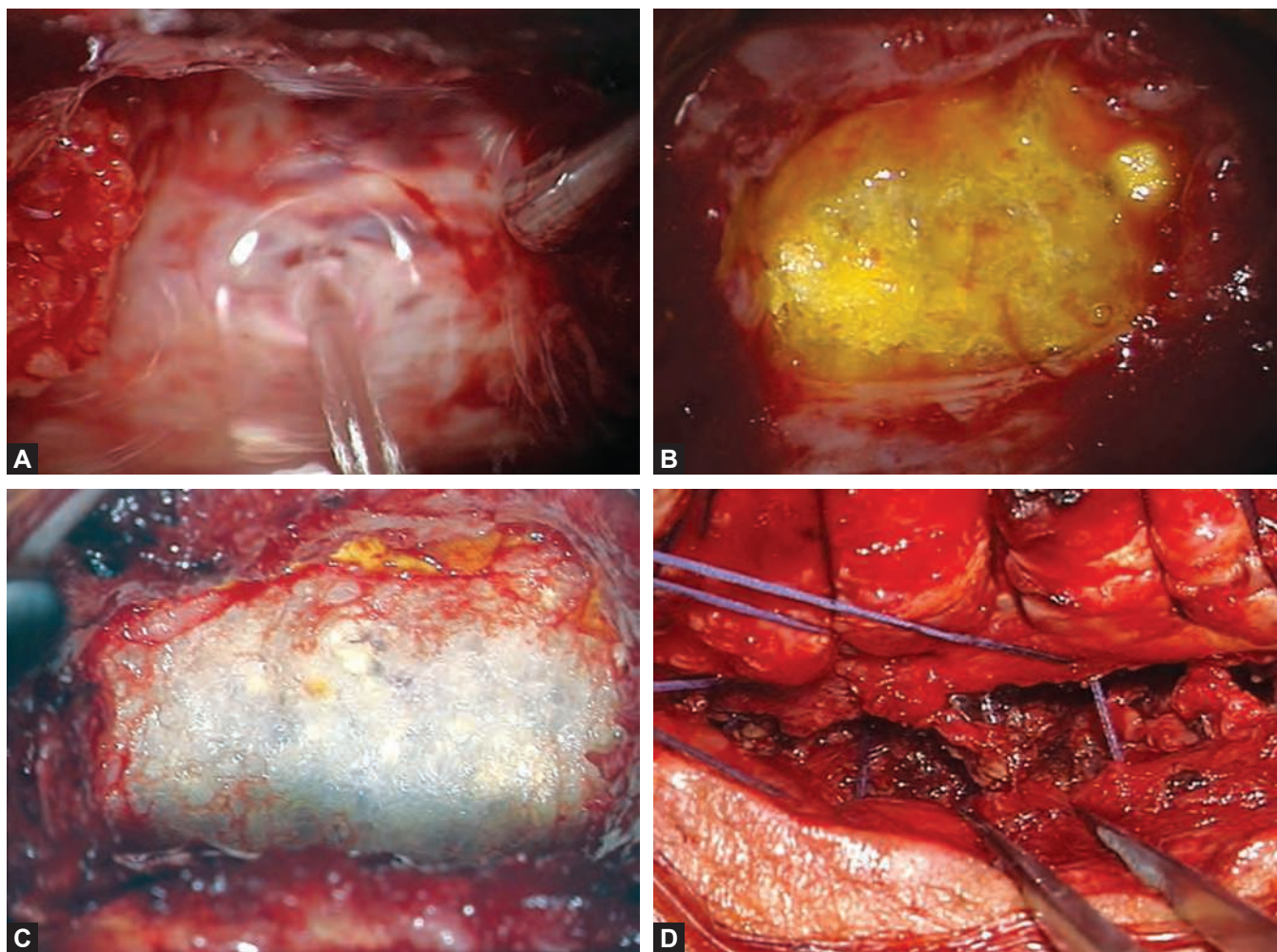
The following acronym “Bird Mc Dove” may aid in remembering a sequence of steps (Figs. 74.10A to D):³⁵

1. **B**one removal until you see the whole dural tear
2. **I**ntradural look
3. **R**epone the nerve roots into the thecal sac, if necessary
4. **D**o an inside patch (e.g. Tachosil with the yellow surface to the dura)
5. **D**ural closure, at best by suturing
6. **O**utside patch (the same as step 4)
7. **V**alsalva maneuver (e.g. 40 cm H₂O × 30 s)
8. **E**pidural pedicled muscle flap (from the paraspinal muscles in order to fill the epidural dead space)
9. **M**ultilayer wound closure (deep muscle layer anchored to the spinous process),
10. **C**erebrospinal fluid drainage, if necessary

Of course not all of the above-mentioned steps are necessary every time. The first goal is to get a watertight closure of the dura (5). Should that fail, then three steps become mandatory: to seal the dural opening (4+6), to achieve a watertight wound closure, (9) and to lower the postoperative CSF pressure (10).²⁹

CRITICAL EVALUATION

“But successful lumbar disc microsurgery is also based on the surgeon’s appreciation of the facts that microsurgery is



Figs. 74.10A to D: (A) Recurrent disc surgery: Intraoperative large dural tear caused by pulling epidural scar tissue. The opening is not suitable for direct repair; (B) The opening has been closed from inside with hemostatic (yellow surface) collagen (Tachosil); (C) The same has been done from the epidural side with the hemostatic yellow surface inside (sandwich technique); (D) A tension-free pedicled epidural muscle flap fills the epidural space. Furthermore, deep anchoring sutures are passed through the spinous process.

not seek-and-find surgery, and that the microscope does not do the surgery.”¹⁸

The first half of the citation stresses the importance of preoperative planning: the careful evaluation of location, size, and shape of the DH, its relationship to the disc space, to the exiting and to the traversing root, to the lateral recess, and to the root or spinal canal requires excellent MRI imaging and dictates the soft-tissue approach and the intraspinal handling of the pathology. A surgical plan tailored for the individual DH becomes necessary. At that point, the small skin incision, reduced muscle traumatization, conservative bone drilling, and plain removal of the offending disc fragment become the practical implementation of the microsurgical philosophy.

The second half of the citation points out that although “small is beautiful,” it should never be an end in itself. Especially at the beginning of the microsurgical learning curve, switching to a larger approach should be considered whenever problems arise. However, with increased experience, all difficult situations will be addressed even more effectively with the aid of the microscope.

The gap that has been bridged between macro- and microsurgery is going to be overcome by the latter and endoscopic spinal techniques. Robotic nanosurgery is waiting behind the corner in the future. The goals do not change: to get a good clinical result with the least iatrogenic trauma.

KEY POINTS

- Even though this chapter has dealt with technical aspects of the surgical treatment of lumbar disc herniations, proper indications with the right technique at the right moment is the most important factor influencing the clinical outcome.
- The use of the microscope provides many advantages.
- The most important aspect of the microsurgical philosophy that supports minimally invasive surgery is the “mental planning” of the procedure beforehand.
- The assumption that one approach fits all subgroups of lumbar disc herniations has been substituted by the conviction that tailored approaches such as the interlaminar, translaminar, and paraspinal approaches address the different pathologies in a less traumatizing manner.
- The use of a paramedian muscle-splitting approach and the use of tubular retractors when available have even further reduced the approach morbidity, especially in obese patients.

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Mc Culloch JA, Young PH. *Essentials of Spinal Microsurgery*, Chapter 20. Philadelphia: Lippincott-Raven; 1998. Microsurgery for lumbar disc herniation; p. 380.
Written by an orthopedic surgeon and a neurosurgeon (quite uncommon at that time!) one and a half decades ago, this book covers the basic principles of microsurgery in an unparalleled way! The sections on the treatment of

lumbar and cervical disc disease are a must for all spine surgeons thinking about utilizing microsurgical techniques.

Mayer HM. Principles of microsurgical discectomy in lumbar disc herniations. In: Mayer HM (Ed). *Minimally Invasive Spine Surgery*. Heidelberg: Springer; 2005. pp. 278-81.

A multiauthored and complete survey of all microsurgical and endoscopic techniques is given. The chapter addresses terminology, history, surgical principles, advantages/disadvantages, indications, access principles, complications, and results, which educates the reader familiar with all types of new minimally invasive techniques in clinical use.

Schiefer W, Klinger M, Brock M, et al. A new surgical procedure for lumbar disc herniation causing less tissue damage through a microsurgical approach. In: *Advances in Neurosurgery*, Vol 4. Berlin: Springer; 1977. pp. 74-80.

The microsurgical treatment of lumbar DH was born and became a new frontier in this article! On page 81-82 of the same Volume of the same Journal, MG Yasargil reported his microsurgical experience with 105 lumbar disc patients. One year later, RW Williams published in *Spine* "Microlumbar discectomy: A conservative surgical approach to the virgin herniated disc."

Foley KT, Smith MM. Microendoscopic discectomy. *Tech Neurosurg*. 1997;3:301-7.

This article reports for the first time the technical aspects of the new procedure. Microendoscopic discectomy is performed by a muscle-splitting approach using a tubular retractor. A specially designed endoscope is placed inside the tubular retractor while the surgeon views the procedure on a video monitor. Nowadays, expandable tubular retractors are available and surgery may be performed with the microscope, thereby shortening the learning curve. The clinical advantage of less traumatization of the muscle tissue and of less bleeding is maintained.

Di Lorenzo N, Porta F, Onnis G, et al. Pars interarticularis fenestration in the treatment of foraminal lumbar disc herniation: a further surgical approach. *Neurosurg*. 1998;42:87-90.

In this paper, the translaminar approach to cranial extruded lumbar disc herniations has been reported for the first time. At that time, the comments enclosed concerns about the limited exposure and the difficulty of the procedure, the potential risk of early or late fracture of the pars interarticularis, and the assumed inability to clear the disc space. Fortunately, 14 years later, this approach has proven to be straightforward, to spare the facet and the yellow ligament, and to be the first choice for the treatment of foraminal DHs.

Cauda Equina and Conus Medullaris Syndrome

Rojeh Melikian, Thomas D Cha

Snapshot

- » Pathophysiology
- » History and Physical Examination
- » Radiographic Evaluation
- » Other Diagnostic Tests
- » Surgical Management
- » Prognosis

INTRODUCTION

Cauda equina syndrome (CES) and conus medullaris syndrome (CMS) are rare neurologic disorders that result from the dysfunction of sacral nerve roots in the vertebral canal resulting in impairment of bladder, bowel, or sexual function. Typical manifestations of CES include low back pain, unilateral or bilateral sciatica, bilateral lower extremity weakness, saddle or perianal anesthesia, as well as rectal and bladder sphincter dysfunction.¹ Typical manifestations of CMS are similar without the motor disturbances in the lower extremities and with sensory disturbances limited to sacral dermatomes.²

Cauda equina syndrome is a rare disorder with equal incidence among males and females. The incidence of CES is variably reported and depends on its etiology. It has been implicated in 2–6% of lumbar disc operations and has been estimated in the general population to occur with an incidence of 1 in 33,000–100,000.^{3–5} Its recognition is often delayed as its manifestations of bladder, bowel, and sexual complaints have a variety of other possible causes. Additionally, a patient's hesitation to mention these symptoms due to embarrassment or because of insidious onset may contribute to the delay in diagnosis. Isolated CMS is even less common than CES and almost always associated with intradural pathology such as tumors or vascular lesions. Compressive lesions at the level of the conus medullaris will almost always compress the cauda equina as well and give rise to a mixed picture.

PATHOPHYSIOLOGY

The spinal cord terminates at approximately the level of the intervertebral disc between first and second lumbar vertebrae and forms the conus medullaris. The conus medullaris consists of the myelomeres of the five sacral nerve roots and represents a transition zone from central to peripheral nervous system. Whereas the roots of the upper cervical nerves maintain their initial embryonic position, the progressive differential growth between the cord and spinal column pulls the lumbosacral roots inferiorly in an increasingly oblique direction. The cauda equina consists of this bundle of nerve roots distal to the conus medullaris, which have been drawn inferiorly during fetal development. The motor fiber components of each nerve root are found anteromedially and the larger sensory components are located posterolaterally.⁶

The pathophysiology behind CES is at present still unclear. Arterial injection studies have suggested that each lumbosacral root receives its own blood supply from both distal and proximal radicular arteries that anastomose in the proximal one third of the root. This forms an area of relative hypovascularity, which predisposes lumbosacral roots to injury from compression.⁷ In addition, the small nerve fibers that transmit pain and parasympathetic function are more susceptible to mechanical compression than the larger nerve fibers that transmit motor, light touch, and proprioception.³ Unlike peripheral nerve fibers that have a more robust connective tissue covering, the

frail connective tissue that invests the lumbosacral roots provides little mechanical protection from compression. Other predisposing factors to CES and CMS include a congenitally narrow spinal canal or acquired spinal stenosis from degenerative changes.

The pathophysiologic mechanisms in development of CES may be related to direct mechanical compression, inflammation, venous congestion, or ischemia. Histologic examination of compressed nerve roots has shown dilatation of intradiscal veins with an inflammatory cell infiltrate.⁶ Sekiguchi et al.⁸ conducted a study showing endothelial cell dysfunction leading to contraction of blood vessels in nerves under chronic compression. Lee and Wolfe⁹ postulated that nerve root compression led to disruption of the blood-brain barrier and allowed antigenic proteins to enter the central nervous system. This in turn triggers an autoimmune inflammatory response leading to demyelination and degeneration. Rydevik et al.¹⁰ demonstrated mechanical compression of roots causing intraneural edema, resulting in increased intraneural pressure and decreased perfusion. One or more of these mechanisms are likely the cause of nerve root dysfunction in CES and CMS.

Bladder dysfunction is a hallmark of CES and CMS. The detrusor muscle of the bladder as well as the internal sphincter is controlled by the parasympathetic nerves that travel along the S2-S4 nerve roots. Parasympathetic innervation promotes bladder emptying by contracting the detrusor muscle and relaxing the internal sphincter. The external sphincter of the bladder, which is a striated muscle under voluntary control, is innervated by the pudendal nerve, which is also formed by fibers from the S2-S4 roots. Compression of the micturition center inside the conus medullaris or the roots causes loss of sensation to the bladder and subsequent inability to detect bladder fullness. In addition, loss of detrusor muscle and sphincter innervation causes inability to voluntarily empty the bladder and eventually leads to overflow incontinence.

Any compressive lesion can cause CES and CMS. The most common cause of CES is compression from central lumbar disc herniation at the L4-L5 or L5-S1 level.^{1,11,12} It may also be caused by spinal stenosis, epidural abscesses, neoplastic processes, traumatic injuries, infection, post-surgical hematomas, ankylosing spondylitis, lumbar punctures, chiropractic manipulation, and spinal or epidural anesthetics (Table 75.1).¹³⁻¹⁵ As mentioned previously, pure CMS can be caused by intradural tumors or vascular lesions, but is unlikely to be caused by extradural compression as this results in compression of the cauda

Table 75.1: Causes of cauda equina syndrome.

Degenerative	Disc herniation Spinal stenosis
Infectious	Epidural abscess
Hemorrhagic	Epidural hematoma Subdural hematoma
Trauma	Spinal surgery
iatrogenic	Spinal or epidural anesthesia Chiropractic manipulation
Tumor	Rheumatoid arthritis
inflammatory	Ankylosing spondylitis

equina as well. More commonly, CMS occurs as a mixed picture with CES when caused by extrinsic compression.²

HISTORY AND PHYSICAL EXAMINATION

Early diagnosis of cauda equina and CMS is crucial to prevent irreversible neurologic damage, but can be difficult. The initial signs and symptoms may be subtle and may evolve slowly over time. Symptoms such as urinary issues and sexual dysfunction are also easily attributed to other pathologies. In addition, the clinical symptoms may vary depending on level of pathology and number of nerve roots affected. Further complicating the diagnosis is the reluctance of patients to discuss certain findings such as erectile dysfunction or bowel and bladder incontinence, out of fear of embarrassment. Patients may frequently have insidious onset of symptoms or a long history of chronic back pain and may not be alarmed by their initial symptoms. The diagnosis is made on clinical grounds with radiologic studies used to define the type of compressive etiology, localize the level, and to assist in surgical planning.

Cauda equina syndrome has been described as having three classic patterns of presentation.^{5,16} It can present acutely as the first symptom of a herniated lumbar disc in a patient without previous history of back problems (type 1), acutely after a long history of chronic back pain and sciatica (type 2), or over a long period of time with slow progression of symptoms (type 3).

The aim of the initial history is to delineate the nature and chronicity of symptoms, possible etiologies as well

Table 75.2: Characteristics of conus medullaris and cauda equina syndromes.

	<i>Conus medullaris syndrome</i>	<i>Cauda equina syndrome</i>
Motor strength	<ul style="list-style-type: none"> No lower extremity weakness 	<ul style="list-style-type: none"> Level of compression <ul style="list-style-type: none"> <i>Pathology at L2 level:</i> Can affect all lumbosacral roots except L1 and result in motor weakness and decreased sensation below inguinal crease <i>Pathology at L4 level:</i> Preserved quadriceps strength and patellar reflexes with intact sensation down to L3 dermatome <i>Pathology at S2 level:</i> No lower extremity manifestation
Reflexes	<ul style="list-style-type: none"> Patellar and achilles reflexes unaffected Bulbocavernosus and anal wink reflex diminished 	<ul style="list-style-type: none"> Level of compression <ul style="list-style-type: none"> <i>Pathology at L2 level:</i> Decrease in all lower extremity reflexes <i>Pathology at L4 level:</i> Preserved patellar reflex with diminished Achilles reflex <i>Pathology at S2 level:</i> No lower extremity manifestations Any of the above level of compression can affect the downstream sacral roots and cause loss of anal wink and bulbocavernosus reflexes
Sphincter dysfunction	<ul style="list-style-type: none"> Atonic bladder Flaccid anal sphincter 	<ul style="list-style-type: none"> Atonic bladder Flaccid anal sphincter
Sensory	<ul style="list-style-type: none"> Perineal anesthesia 	<ul style="list-style-type: none"> Perineal anesthesia Loss of sensation in specific dermatomes of lower extremity depending on level of compression
Radicular pain	<ul style="list-style-type: none"> No radicular pain 	<ul style="list-style-type: none"> Symptoms dependent on level of compression

as bowel, bladder, and sexual function.⁶ Up to 62% of patients will report a recent history of trauma with the most common inciting events being weight-lifting, falls, or motor-vehicle accidents.^{12,17-19} Other risk factors include a history of cancer, infection, anticoagulation, and previous spinal surgeries. In most cases, the most common symptoms are back pain and radiculopathy.²⁰⁻²² This contributes to the difficulty in diagnosing CES as the majority of patients have had back pain or sciatica prior to presentation; however, in acute-onset CES, there is a sudden increase in the intensity of the back pain.

The manifestations of CES in the lower extremities will vary depending on the level of pathology. Pathology at the L2 level will affect all lumbosacral roots except L1. This can result in lower extremity weakness in all muscle groups as well as decreased sensation below the inguinal creases. In addition, it may cause a decrease in all lower extremity reflexes as well as urinary symptoms. Pathology at the L4 level will have preserved quadriceps strength, normal patellar reflexes, and intact sensation down to the L3 dermatome. With lesions affecting S2 and below, there

will be no lower extremity manifestations; however, there will be saddle anesthesia as well as urinary symptoms. This presentation is similar to CMS and clinically it is difficult to differentiate the two (Table 75.2).

The key to differentiating CES and CMS from an acute disc herniation or exacerbation of chronic pain lies in elucidating sacral nerve root dysfunction. The development of saddle anesthesia, bowel or bladder dysfunction, or sensorimotor deficits in the lower extremities should raise suspicion for these syndromes. Initial urinary irritative symptoms progress to altered urinary sensation and loss of a desire to void. With continued compression, there is a progression to painless urinary retention with overflow incontinence. Once compression has existed long enough to produce this level of dysfunction, the deficits are unlikely to recover despite decompression.^{3,23} Sexual dysfunction has been noted to be present in <5% of patients on presentation, but has been documented at around 30% in long-term follow-up. This difference may stem from patient's reluctance to disclose this at the time of presentation as well as the ease with which it can be attributed to

other causes.^{17,21,24} Sexual dysfunction can consist of erectile dysfunction, ejaculatory dysfunction, and decreased sensation during intercourse. Patients may be hesitant to volunteer such information and clinicians will need to specifically ask to elucidate these symptoms. Bowel dysfunction in patients may not always be evident as it ranges from lacking a sense of rectal fullness to frank inability to control defecation and is most often not as troubling to patients as their urinary symptoms.

Further adding to the diagnostic dilemma are documented cases of CES without complaints of bowel or bladder dysfunction. Urodynamic studies have shown patients can have disturbances in bladder function, which are subclinical.²⁵ The diagnosis in these cases was made on the basis of sexual dysfunction, saddle anesthesia, and bilateral lower extremity symptoms.^{13,26,27}

In terms of physical examination, a full neurologic examination, including perianal sensation and assessment of rectal tone, should be performed whenever CES or CMS is suspected. Sensory deficits most commonly occur over the perineal region, buttocks, and posterior thighs.²⁸ Seventy-six percent of patients presenting with CES will have decreased perianal sensation.²¹ Pinprick sensation should be tested in addition to light touch, as patients will often have intact light touch but diminished pinprick sensation.²⁹ This can be explained by proximity of the spinothalamic tracts to the autonomic tracts supplying the bladder. Complete perineal anesthesia to both light touch and pinprick at presentation has been shown to be a poor prognostic sign.³⁰ Motor deficits in CES can be of varying degrees from minor disturbances to paresis. Most commonly motor deficits are minimal if present at all.

With regard to reflexes, there is no consensus in the literature about pattern of reflexes in CES. Patients may have diminished or absent patellar or Achilles reflexes, but involvement is variable depending on the level of pathology. Compression of the conus medullaris should have no effect on lower extremity reflexes. Both CES and CMS can cause loss of bulbocavernosus reflex and anal wink reflex as these are sacral root mediated. The preservation of bulbocavernosus reflex is a good prognostic sign as it indicates an intact arc between pelvic afferents and sacral efferents.²

Once the diagnosis is established, an important clinical distinction is dividing CES into two stages of presentation as it affects both the urgency of management and

the prognosis. The first stage is incomplete cauda equina syndrome (CES-I), in which there are urinary symptoms such as altered sensation, poor stream, and loss of desire to void but no established retention. The second stage occurs as patients develop painless urinary retention and overflow incontinence (CES-R).³ Patients with established urinary retention at presentation have a much poorer prognosis than those who present with urinary issues but no established retention.

During patient evaluation, the differential diagnosis for presentations similar to CES and CMS should be kept in mind. This includes exacerbation of low back pain, lumbar disc herniation, peripheral neuropathy, diabetic neuropathy, acute inflammatory demyelinating polyneuropathy, neoplastic processes, traumatic injuries, and Guillain-Barre syndrome.

RADIOGRAPHIC EVALUATION

Radiologic investigations into CES and CMS can include plain radiography, myelography, computed tomography (CT), CT myelography, and magnetic resonance imaging (MRI). Plain X-rays are often the first study obtained for patients presenting with spine-related issues but are of limited value in evaluating CES. They can, however, reveal disc space narrowing suggestive of herniation, destructive changes due to neoplastic or infectious processes, as well as traumatic injury to the spinal column.

Plain myelography can be useful in identifying the site of compression, but shows far less detail than CT myelography and MRI. It is rarely used other than in resource poor settings where CT and MRI are unavailable.

Magnetic resonance imaging is the imaging modality of choice for assessing CES. It avoids the ionizing radiation of CT as well as the invasive nature of myelography. In addition, it can provide excellent resolution of any space-occupying lesions as well as delineate the degree of compression of neural structures.³¹

In patients unable to get an MRI, CT myelography is the imaging study of choice and can assist in identifying the site of compression. It has roughly equivalent sensitivity and specificity to MRI and can be performed in patients with pacemakers or other contraindications to MRI.³²

OTHER DIAGNOSTIC TESTS

The micturition center of the spinal cord is located at the S2-S4 levels. If the diagnosis is unclear, attempts at diagnosing detrusor dysfunction can be undertaken. Postvoid

residuals may be measured either with foley placement or bladder scans after voiding. Healthy volunteers have been noted to have <30 cc on postvoid residuals, whereas values of 100 cc or more are suspicious for urinary retention.³³

An additional diagnostic test that can be performed at the same time is the trigone sensitivity test. An inflated foley catheter is gently pulled and should produce the urge to urinate. Presence of trigone sensitivity may be used as an aid to differentiate between complete and incomplete CES.

Some authors have recommended preoperative urodynamic studies as a method of assessing detrusor activity and to assist in differentiation of CES-R and CES-I.^{34,35} These studies are also helpful in the postoperative period to document level of impairment. Obtaining these studies preoperatively can be done, but only if they will aid in the diagnosis and can be obtained expeditiously. Surgical decompression should never be delayed in an attempt to obtain urodynamic testing preoperatively.

SURGICAL MANAGEMENT

When a patient is diagnosed with CES or CMS and has a potentially reversible cause of compression, surgical decompression is the treatment of choice. The timing of surgical decompression remains the most important issue as well as one of the most controversial. It is not possible ethically to design a randomized study to examine early versus late decompression. In a retrospective review, Gleave and MacFarlane²³ concluded emergency decompression is only indicated in patients in the incomplete stage of CES (urinary symptoms but no established retention). It was noted that patients with established urinary retention and incontinence at presentation have poor clinical outcomes independent of time to surgery and require urgent but not emergent decompression so as to avoid trips to the operating room under less than ideal circumstances. Additional research has been done, which also supports this conclusion with regard to timing.^{21,36,37} However, some authors have advocated for emergent surgery with the reasoning that a damaging process to the neural elements should be addressed as soon as possible.^{16,38,39}

Ahn et al.¹² as part of a large meta-analysis looked at several factors including time from presentation to surgical decompression. Patients with preoperative rectal dysfunction or history of preoperative chronic low back pain were at an increased risk of continued postoperative urinary incontinence. The prognosis for rectal function after surgery worsened with a history of chronic low back pain.

In terms of time to decompression, the authors found increased risk of continuing urinary deficit, motor deficit, rectal dysfunction, and sensory deficit in the group decompressed at >48 hours as opposed to those who were decompressed earlier. They found no statistically significant difference between patients decompressed within 24 hours and those who were decompressed between 24 and 48 hours. Additionally, they found no difference in outcome with respect to resolution of pain, sensory and motor deficits, and urinary, rectal, and sexual dysfunction in patients who underwent decompression at >48 hours after symptom onset. They concluded that patients with CES/CMS should be decompressed within 48 hours, but that decompression within 24 hours showed no benefit. However, Kohles et al.⁴⁰ reviewed the statistics in this meta-analysis and concluded that due to small sample size and flawed methodology, they likely underestimated the value of early surgical decompression.

In a meta-analysis by Todd³⁹ looking at time from symptom onset to surgery with respect to resumption of socially normal bladder function, there was stronger evidence for the 24-hour rather than the 48-hour window for improving urologic outcomes.

In terms of operative planning, surgical treatment should be focused on alleviating the underlying compressive etiology. In general, the accepted surgical technique for treatment of CES or CMS is wide laminectomy, removal of the offending disk, hematoma or other space-occupying lesion as well as foraminotomies if needed for stenosis.^{17,20,36,40,41} Some authors have reported treatment through laminotomies, but this is currently not recommended as it requires additional traction on already compressed neural elements.⁶ Anterior decompression can be considered in the presence of vertebral body destruction from etiologies such as tumor or large abscess.

PROGNOSIS

The prognosis for CES and CMS depends on several factors including etiology, duration of symptoms, acuity of onset, number of spinal levels involved, and degree of neurologic deficit on presentation. The severity of bladder dysfunction at the time of surgery was a dominant factor in bladder function recovery in a study by Qureshi and Sell.³⁷ They performed a prospective longitudinal study that found a poorer prognosis for those patients with established urinary retention at presentation. Those with incomplete cauda equina at presentation had better urologic outcomes as well as significantly less likelihood of

back and leg pain at long-term follow-up. These results were supported by several other studies, which concluded the severity of bladder or anal sphincter disturbance at presentation were predictors of overall residual dysfunction after surgery.^{3,16,23,30,37,42} A study by Kennedy et al.,³⁰ did not find any predictive value in the severity of initial motor dysfunction, bilateral sciatica, or the level of injury. While there was a correlation between more rapid onset of symptoms and poorer outcomes, this finding did not reach statistical significance ($P = 0.052$).

No studies found a difference in prognosis with the level of herniation, but there has been evidence to suggest that involvement of the lower sacral nerve roots manifests with clinical symptoms, which are more subtle than cases that involve lumbar roots and are, therefore, more prone to delay in diagnoses.⁴³

With regard to overall recovery from CES, McCarthy et al.²¹ reviewed 56 cases and concluded patients do not return to normal status based on SF-36, Oswestry Disability Index (ODI), and Low Back Outcome Scores; however, subjective recovery of bladder and sexual function may continue for years following treatment of CES and has been attributed to the patient's ability to develop compensatory strategies.^{44,45} Approximately 75% of all CES cases eventually regain acceptable urologic function, but are frequently left with chronic back pain and lower limb as well as perineal sensory deficits.²³ The remaining percentage of CES patients will have poor outcomes and will need multidisciplinary treatment for ongoing urologic, bowel, and sexual dysfunction.

KEY POINTS

- Cauda equina syndrome and CMS are rare neurologic disorders that result from the dysfunction of sacral nerve roots in the vertebral canal, resulting in impairment of bladder, bowel, or sexual function.
- The most common cause of CES is compression from central lumbar disc herniation at the L4-L5 or L5-S1 level.
- A high index of suspicion is needed to diagnose CES and CMS. Symptoms such as urinary issues and sexual dysfunction are also easily attributed to other pathologies. Patients may frequently have insidious onset or a long history of chronic back pain and may not be alarmed by their initial symptoms.
- Magnetic resonance imaging is the imaging modality of choice to delineate a compressive lesion.

Computed tomography myelography can be performed in those who have contraindications to MRI.

- In patients with incomplete CES (urinary symptoms, but no established urinary retention), surgical decompression should be undertaken as soon as safely possible and at least within 24 hours. No data exist to elucidate the difference between emergent decompression and those which occur within 24 hours. However, in the absence of further data, emergent decompression should be considered as soon as adequately skilled personnel and infrastructure are available, with the goal being to prevent progression to established urinary retention. Those with established urinary retention at presentation require urgent, but not emergent decompression.

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Ahn UM, Ahn NU, Buchowski JM, et al. Cauda equina syndrome secondary to lumbar disc herniation: a meta-analysis of surgical outcomes. *Spine (Phila Pa 1976)*. 2000; 25(12):1515-22.

Large meta-analysis that looked at several factors including time from presentation to surgical decompression. The authors found increased risk of continuing urinary deficit, motor deficit, rectal dysfunction, and sensory deficit in the group decompressed at >48 hours as opposed to those who were decompressed earlier. They found no difference between the 0-24-hour group and the 24-48-hour group. Additionally, they found no difference in outcome in any groups decompressed after 48 hours. They concluded that patients with CES/CMS should be decompressed within 48 hours, but that decompression within 24 hours showed no benefit.

Gleave JR, MacFarlane R. Prognosis for recovery of bladder function following lumbar central disc prolapse. *Br J Neurosurg*. 1990;4(3):205-9.

In a retrospective review, Gleave and MacFarlane noted that patients with established urinary retention and incontinence at presentation have poor clinical outcomes independent of time to surgery. Therefore, those with established retention at presentation require urgent but not emergent decompression so as to avoid trips to the operating room under less than ideal circumstances. Emergent decompression should only be considered in patients with incomplete cauda equina syndrome (urinary symptoms, but no established urinary retention).

Kennedy JG, Soffe KE, McGrath A, et al. Predictors of outcome in cauda equina syndrome. *Eur Spine J*. 1999;8(4): 317-22. Retrospective review of predictors of outcomes in cauda equina syndrome. The authors found no predictive value in the severity of initial motor dysfunction, bilateral sciatica, or the level of injury. They did find a correlation between more rapid onset of symptoms and poorer outcomes, but this did not reach statistical significance ($P = 0.052$). Similar to other studies, they found that the severity of bladder dysfunction at time of presentation was a predictive factor for postoperative bladder function.

Qureshi A, Sell P. Cauda equina syndrome treated by surgical decompression: the influence of timing on surgical outcome. *Eur Spine J*. 2007;16(12):2143-51.

Prospective longitudinal study that found poorer prognosis for patients with established urinary retention at presentation. Those with incomplete cauda equina at presentation had better urologic outcomes as well as significantly less likelihood of back and leg pain at long-term follow-up. Thus, the severity of bladder dysfunction at the time of surgery was the dominant factor in bladder function recovery as well as long-term back and leg pain.

Todd NV. Cauda equina syndrome: the timing of surgery probably does influence outcome. *Br J Neurosurg*. 2005; 19(4):301-6; discussion 7-8.

Meta-analysis of cauda equina syndrome cases looking at time from symptom onset to surgery with respect to resumption of socially normal bladder function. The authors found stronger evidence for decompression within the 24-hour rather than the 48-hour window in order to improve urologic outcomes.

Lumbar Nucleus Pulposus Replacement

Timothy Roberts, James P Lawrence

Snapshot

- » Anatomy and Physiology of the Normal Intervertebral Disc
- » Pathophysiology and Natural History of the Degenerating Intervertebral Disc

- » Disc Replacement Strategies

INTRODUCTION

Low back pain (LBP) remains an extremely common entity, affecting approximately 85% of adults during their lifetimes.¹ As many as 40% of this group² are believed to have pain generated by abnormalities attributable to the intervertebral disc. While the proportion of patients requiring surgical intervention for the treatment of so-called degenerative disc disease (DDD) is low, nonsurgical methods can be ineffective, procedural options are limited, and outcomes remain unpredictable.

Disc degeneration results from a complex pathophysiologic cascade likely triggered by an acute injury or insult to the disc-endplate complex. The consequences are impaired diffusion and transport of key nutrients to the nucleus pulposus (NP), followed by its degeneration and dysfunction.³ The nuclear environment cannot be maintained by the production of adequate proteoglycans and noncollagenous proteins, and the nucleus fails both biochemically and mechanically. The NP also improperly interacts with the annulus fibrosus, causing painful annulus degeneration, disc collapse, reactive bony changes, osteophyte development, increased stress on adjacent joints, instability, and potentially both cord and nerve root compression.

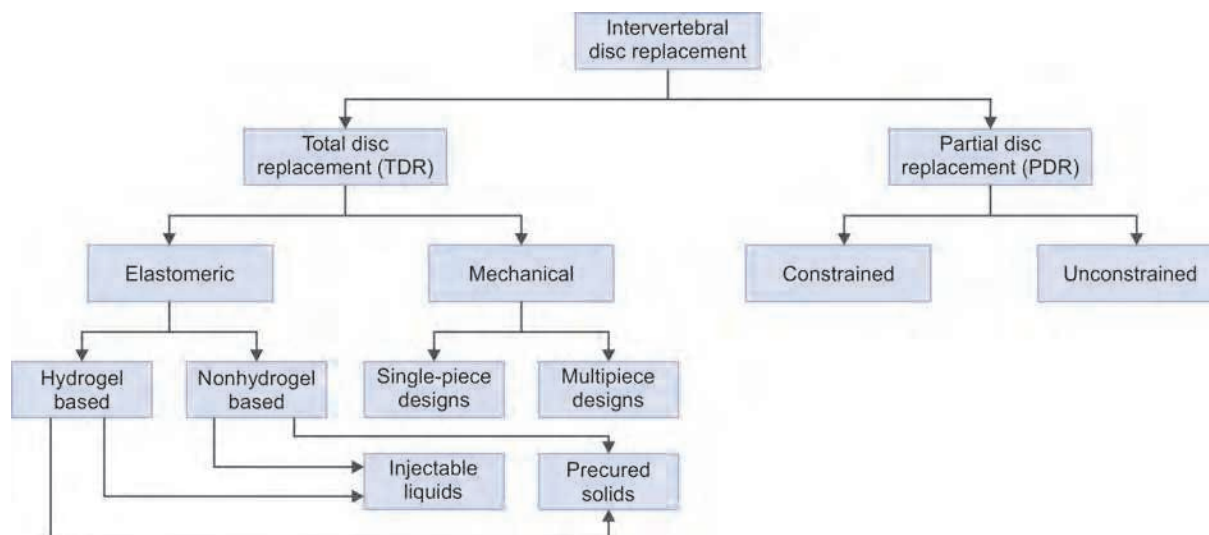
The current standard of care for painful disc degeneration is conservative, with the utilization of nonsteroidal anti-inflammatory drugs, physiotherapy, chiropractic care, and occasionally pain management if a particular “pain

generator” can be identified. From a surgical perspective, options are limited in scope and questionable in terms of effectiveness, and include discectomy and fusion, discectomy and arthroplasty, or derivations of the above. Unfortunately, these options cannot fully address the underlying dysfunction of the nucleus, restore its function, or halt the progression of the degenerative cascade.

Lumbar NP replacement or partial disc replacement (PDR) is a procedure in which the diseased NP is exchanged with a synthetic implant in an attempt to address pain, maintain motion, restore functional loading capacity, and restore the physical parameters of the NP. Unlike total disc replacements (TDRs), PDRs are intended to replace the NP with preservation of the annular, cartilaginous, and bony endplate components of the disc. The potential benefits of PDR over fusion include the restoration of physiologic or near-physiologic motion, the reduction of stresses on adjacent segments, and the avoidance of fusion-related challenges with regard to the consequences to adjacent segment, osseous union, graft harvesting, and/or controversial orthobiologics.

ANATOMY AND PHYSIOLOGY OF THE NORMAL INTERVERTEBRAL DISC

The intervertebral disc is composed of the peripheral annulus fibrosus, the central NP, and the surrounding cartilaginous endplates. The annulus fibrosus is a thick fibrous

Flowchart 76.1: Taxonomy of disc replacement strategies.

Source: Adapted from Coric D, Mummaneni PV. "Classification of nucleus replacement devices" in nucleus replacement technologies: invited submission from the Joint Section Meeting on Disorders of the Spine and Peripheral Nerves. *J Neurosurg Spine*. 2008;8:115-20.

band consisting of predominantly type I collagen that functions to effectively contain the more gelatinous nucleus within the intervertebral space (Flowchart 76.1). The border between the annulus and nucleus does not exist as a distinct boundary, but has a gradual transition. Fibrous bands of the annulus predominate at the periphery of the disc, but the composition becomes more semi-solid toward the center.³

The NP is composed of type II collagen, mucopolysaccharides, and glycosaminoglycans. The hydrophilic proteoglycans provide a strong osmotic gradient that is able to absorb and sequester water. The nucleus optimally flexes and interacts with the surrounding annulus fibrosis in its hydrated state. These two essential properties define the challenges of effective nucleus replacement.

The vertebral endplate is composed of a thin layer of hyaline cartilage and the underlying bony endplate. The hyaline cartilage, predominantly also type II collagen, serves to maintain the disc metabolism by restricting water and proteoglycan exit from the nucleus while permitting the passage of small molecules through diffusion and fluid flow. Diffusion flows follow concentration gradients and allow the passage of molecules like glucose and oxygen. Fluid flow and the passage of larger molecules such as proteins are assisted by mechanical loading.⁴

Biomechanically, the nucleus serves as a fluid "cushion," which both resists and transfers compressive forces to the endplates and encompassing annulus. The annulus, by

contrast, resists tensile, torsional, and radial (hydrostatic) forces as they are applied under loading conditions. Under spinal compression, the generated hydrostatic pressure within the NP is restrained by the hoop stress tolerated by the annulus. Healthy discs exhibit viscoelastic properties, meaning they undergo both elastic changes and time-dependent changes depending on the applied load. Synthetic nucleus replacements, then, must be stiff and viscous enough to withstand compressive forces without migrating or extruding, yet compliant enough to expand radially under pressure, thus dissipating loads between the endplates and the preserved annulus.³

PATHOPHYSIOLOGY AND NATURAL HISTORY OF THE DEGENERATING INTERVERTEBRAL DISC

There is an appreciable difference in the water content of the intervertebral disc that occurs with aging. In the young, water comprises up to 80% of the NP. With normal aging, this declines secondarily to a gradual change in the production of hydrophilic proteoglycans. Additionally, nutritional transport decreases along with the concentrations of large aggregated proteoglycans, the absolute number of viable cells, and pH. Concurrently, there is an increase in small nonaggregated (i.e. less hydrophilic) proteoglycans, concentrations of keratan sulfate, lactic acid, and degradative enzyme activity.⁵

Although the absolute quantity of collagen does not significantly change with degeneration, conversion of relatively hydrophilic type II collagen-based cartilages to fibrocartilage occurs. The NP becomes more fibrous in nature and loses significant osmotic potential.⁶ Histologic degenerative changes are apparent as early as the third decade of life. As the NP dehydrates, it loses its gelatinous consistency and decreases in volume—these changes are manifested as the generalized loss of height with aging, beginning, on average, in the fifth decade of life.

In addition to changing its shape and size, dehydration of the NP alters its biomechanics. The desiccated disc can no longer transfer radial forces to the annulus. Under compressive loads, the otherwise healthy annulus buckles, with its peripheral fibers bulging outward and its inner fibers folding inward. With repetitive cycles, this aberrant motion causes splitting, tearing, and weakening of the annulus. As annular tears propagate, not only does the risk of NP herniation escalate, but also essential fluids and nutrients escape from the formerly enclosed disc space.⁶ The pumping mechanism by which the disc receives nutrients is lost along with its regenerative potential. Finally, because the nociceptive nerve fibers innervating the disc are located within the outer third of the annulus, this process may cause significant and chronic discomfort. Liberated nutrients, metabolites, and inflammatory mediators irritate the peripheral innervation of the annulus.

The degenerated disc decreases in height and becomes intrinsically more rigid and less pliant. This culminates in a mechanical decrease in motion, which, in turn, is exacerbated by subjective pains with motion and/or adjacent muscular spasms. The ultimate result is progressive autofusion across the collapsed intervertebral space, with total loss of motion between the vertebral bodies and, eventually, their facets.⁷ Additional degenerative processes may be triggered in adjacent structures, including facet degeneration, facet hypertrophy, osteophyte formation, and thickening/buckling of the posterior ligaments. If these dysplastic secondary changes result in tissue encroachment into the spinal canal, the lateral recesses, or the neural foraminae, it may result in concomitant lumbar stenosis.

■ DISC REPLACEMENT STRATEGIES

Disc replacement strategies are rapidly evolving and feature a variety of designs and material compositions. Regardless of design specifics, however, the major goals of disc replacement are (1) to eliminate the painful dysplastic elements of

the joint, (2) to preserve the natural range of spinal motion and function, and (3) to reduce mechanical stresses on adjacent segments, theoretically reducing, if not eliminating, adjacent segment degeneration and/or disease.

Disc replacement strategies may be divided into TDR and PDR, also known as nucleus replacement. Total disc replacements aim to replicate the combined function of the annulus and NP, and, for the most part, the endplate as well, while PDRs are annulus-sparing. Flowchart 76.1 displays the array of disc replacement strategies organized by function and composition.

Partial Disc Replacement

The hydrated, semi-solid NP functions to distribute compressive forces cranially and caudally to the endplates, and radially to the annulus. Under axial loading conditions, the disc effectively converts compressive forces into the tensile forces conferred on the outward-bulging annulus. In biomechanical experimental models in which the NP has been removed, axial loads lead to buckling of the annulus, with the outer layers bulging outward and the inner layers caving inward.⁸ Additionally, load is shifted posteriorly, causing the facets to bear supraphysiologic loads. Providing a substitute for the damaged or absent NP may therefore restore the natural kinematics of the normal functional spinal unit (FSU), preventing further damage to the annulus and relieving strains on the posterior facets.

Partial disc replacement poses an attractive potential surgical option for relatively young, healthy patients with symptomatic single-level early DDD. While current surgical standards such as fusion or even TDR might prove overly invasive solutions, PDRs function to replace only the diseased nucleus and may serve to preserve both the intact annulus and the motion segment.⁹ Additionally, PDR can theoretically be performed with minimally invasive or percutaneous techniques and through a greater variety of surgical approaches than TDRs, including anterior transperitoneal, retroperitoneal, lateral, trans-sacral, and/or posterior approaches, depending on the device. Many proponents advocate PDR as a revision option for postpartial discectomy patients with recalcitrant radiculopathy;¹⁰ and some PDR implants are being used to augment primary discectomy techniques.

Partial disc replacement designs in development encompass a broad variety of design philosophies, accounting for at least 25 unique devices in preclinical or clinical testing as of 2007.¹¹ Partial disc replacement strategies can be functionally divided into two groups: elastomeric and mechanical.

Elastomeric devices generally attempt to replicate the natural function of the NP. Mechanical devices side-step attempts to reproduce the material properties of the native disc and instead employ stiffer, more durable materials to maintain both motion and the height of the disc space.

Along with the mechanical properties of any PDR implant, the geometry of the implanted nucleus also plays an essential role in its potential effectiveness. In human cadaver studies, Joshi et al. demonstrated that variations in the shape and volume of the implant influenced the stiffness of the FSU to a greater degree than the implant modulus of elasticity.⁹ Modifications to implant height and diameter were more influential over FSU stiffness than changing the implant modulus by over two orders of magnitude. This suggests that the geometry of the implant, especially its final diameter, plays an essential role in promoting optimal annulus function in vivo.¹² Several finite element analyses have confirmed the restoration of compressive biomechanics of PDS and suggested even that a larger volume implant, even an “overfilled implant,” more accurately restores the compressive biomechanics of the NP.^{13,14}

Table 76.1 summarizes some of the major PDRs under development with reference to their design, composition, material properties, containment, manufacturer, stage of development, and respective potential advantages and disadvantages. While many are still in preclinical development, most of those included have passed various European and/or Asian government standards for investigative use. Several products have obtained US Food and Drug Administration (FDA) approval under the Investigational Device Exemption (IDE), meaning they can be used in a limited number of patients to assess the safety and efficacy of the premarket product.¹⁵

Elastomeric PDR Devices

Elastomeric PDR devices are NP substitutes composed of a wide variety of viscoelastic materials. Elastomeric PDRs aim to recreate the functions of the healthy NP with regard to the interaction with the annulus, the dissipation of stress, and absorption of axial compressive load. Materially, elastomeric devices can be divided into hydrogels (materials with strongly hydrophilic properties) and nonhydrogels. Both hydrogel and nonhydrogel derivatives are available as injectable liquids and precured solids. Finally, elastomeric PDRs may be contained or uncontained, defined here as the presence or absence of an outer volume-limiting casing.

The major challenge for elastomeric PDRs is to provide a device that adequately mimics the mechanical properties of the native NP. Insufficiently stiff implants may lead to an underconstrained motion segment that increases stress on the adjacent discs and, potentially, unwittingly fosters degeneration. Conversely, an excessively stiff material may lead to implant subsidence through the endplate and thus failure of the motion segment.¹⁶

There are two main mechanical properties that require consideration for NP-replicating devices: the modulus of the device (slope of its stress-strain curve through its elastic region) and its corresponding Poisson's ratio. Poisson's ratio quantifies the horizontal expansion of a material under vertical stress, and is expressed as the ratio of lateral strain to axial strain and is unitless. Healthy human NPs have been determined to possess an approximate modulus (the stiffness of a material at equilibrium with surrounding fluid) of a healthy human NP has been shown to equal 1.01 ± 0.43 MPa¹⁷ with a Poisson's ratio of 0.62.¹⁸

Among the criticisms of elastomeric devices is the relative potential for fatigue failure when compared to intrinsically more durable metal implants.¹⁹ Yet, despite the still infantile nature of elastomeric clinical testing, we are not aware of a study that has demonstrated fatigue-related changes to the implant, detrimental or otherwise. Several elastomeric devices have been validated in in vitro loading for up to 50 million cycles without evidence of functional compromise.⁸ Long-term clinical data is needed before the true longevity of these devices is evaluated.

Hydrogel Elastomeric PDRs

Hydrogels are synthetic, hydrophilic polymers that absorb various quantities of water inversely proportional to the applied pressure.⁸ Several synthetic hydrogels have been found to have material and water-imbibing properties near equal to those of the healthy NP. The NeuDisc (Replication Medical, Inc, Cranbury, NJ) is a preformed solid hydrogel made from acrylic copolymers and contained by Dacron (polyethylene terephthalate) mesh. Acrylic hydrogels have been confirmed in cadaver motion segment testing to have compressive moduli between 0.55 and 4.28 MPa, depending on the applied load.²⁰ Pilot clinical trials are apparently ongoing.

Nonhydrogel Elastomeric PDRs

NuCore (Spine Wave, Shelton, CT) is a protein polymer synthesized by bacteria via recombinant DNA. This inject-

Table 76.1: Properties, manufacturers, and development status of various partial nucleus replacement technologies.

Delivery form		Con- tained	Composition/ form	Product	Manufacturer/ developer	Regulatory status/avail- ability (as of 1/2013)	Surgical approaches	Comparative advantages	Comparative disadvantages
Elastomeric	Hydrogel	Injectable liquid	Albumin, glutaraldehyde	Biodisc	Cryolife, Kennesaw, GA	CE mark ^{xi}			
		N	Silicone	Percutaneous nucleus replacement (PNR)	Trans1, Inc, Wilmington, NC	European pilot trials (started 2008); On hold in United States. ⁱ	TS	Complete preservation of annulus (TS approach)	
		N	Polyvinyl alcohol/polyvinyl pyrrolidone copolymer	Hydrafil Nucleus Replacement Implant	Synthes Spine, Paoli, PA	Preclinical development ⁱⁱⁱ	TS	Complete preservation of annulus (transosseous approach)	May require proprietary technology for approach
	Precured solid	Y	Polyacrylonitrile, polyacrylamide in polyethylene jacket	Prosthetic Disc Nucleus (PDN), PDN-Solo, Hydraflex	Raymedica, Inc, Bloomington, MN	US FDA IDE approval (Hydraflex) (2006) ⁱⁱ Pilot feasibility study (Hydraflex) ⁱⁱⁱ	Post (PDN/Solo); ALRP (Hydraflex)	Good track record, >5,500 devices implanted to date ⁱⁱⁱ and functional to 50M cycles. ^{iv} Biocompatibility in human studies ^{iv}	Notable extrusion risk with early models; 10% migration-related explants reported
		N	Polyvinyl alcohol	Aquarelle	Stryker Spine, Allendale, NJ	Testing discontinued: adverse clinical events ⁱⁱⁱ	ALRP, Post	Functional up to 40 M cycles. ^{iv}	Possibly discontinued, ⁱⁱⁱ high rates of extrusion in animal testing (20–33%) ^{iv}
		Y	Acrylic copolymer, reinforced with Dacron mesh	NeuDisc	Replication Medical, Inc, Cranbury, NJ	In pilot clinical studies ⁱⁱⁱ		Biocompatible in animal testing ^{iv}	
	Nonhydrogel	Injectable liquid	Silk/elastin copolymer (rDNA-based synthetic)	NuCore	Spine Wave, Shelton, CT	US FDA IDE approval (2006) In clinical studies ⁱⁱⁱ			
		Y	Polyurethane injectable core with polyurethane expandable balloon	Disc Arthroplasty Device (DASCOR)	Disc Dynamics, Inc, Eden Prairie, MN	FDA IDE approval 2006, ⁱⁱ Pilot clinical studies ⁱⁱⁱ	ATP, ALRP, LTP, ± PL ^v	Positive outcomes in 2+ year European trials. ^v Biocompatible in animal testing ^v	
	Precured solid	N	Polycarbonate urethane	Newcure	Zimmer Spine, Minneapolis, MN	Testing discontinued: adverse clinical events, likely secondary to endplate deformities/subsidence ^{iii,vi}		Biocompatible in animal testing, finds own orientation in disc space regardless of insertion, functional at 50 M cycles ^{iv}	Possibly discontinued ⁱⁱⁱ

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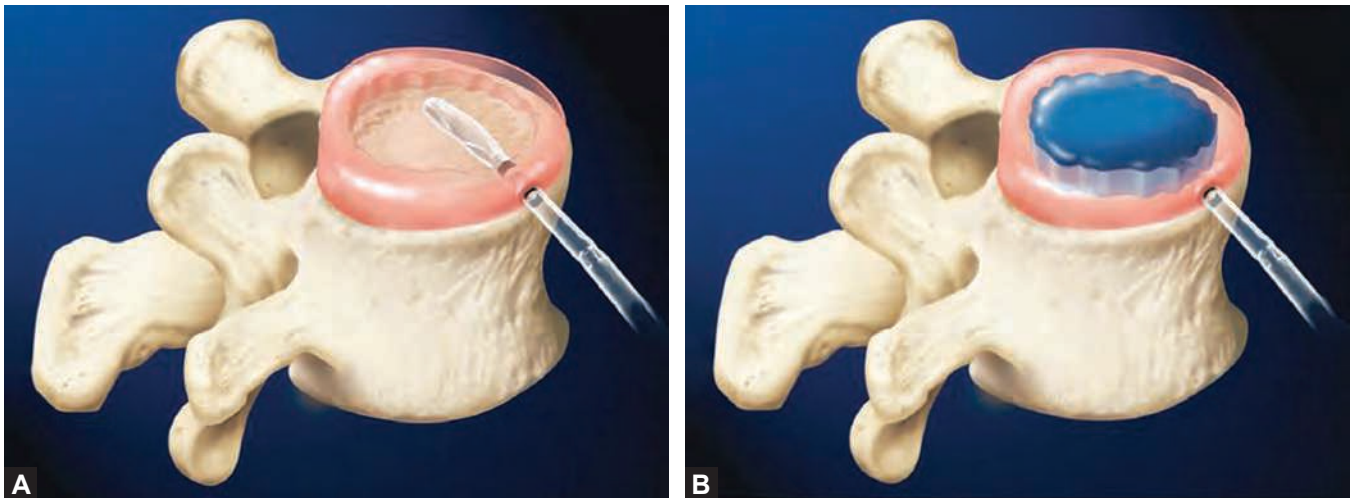
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Mechanical	Delivery form	Con- tained form	Composition/ form	Product	Manufacturer/ developer	Regulatory status/avail- ability (as of 1/2013)	Surgical approaches	Comparative advantages	Comparative disadvantages
	Single-piece		Stainless steel	Fernstrom ball-bearing	n/a	Device discon- tinued; histori- cal reference only			Significant bone- implant modulus mismatch, high- degree subsid- ence, Discontin- ued
			Polyether ether ketone (PEEK) or cobalt chromium interbody spacers	Satellite spinal system	Medtronic Sofamor Danek, Memphis, TN	Approved by FDA 2007 (for fracture fixation; <i>not</i> as motion-sparing implant In clinical trials ^{vii})		Strong, durable mate- rial properties	Unequal force distribution, no shock absorption
	Multipiece		Graphite core with pyrolytic carbon coat	Regain	Biomet/EBI Medi- cal, Parsippany, NJ	CE mark Japanese IDE approval	ARP, LTP (L4-L5, L5-S1)		L4-L5, L5-S1 only
			PEEK-on-PEEK ball-socket	NuBac	Pioneer Surgical Technology, Inc, Austin, TX	US FDA IDE approval (2006), ⁱⁱ Passed CE ⁱ	LTP (L3-L4, L4-L5), ARP (L5-S1), Post (L5-S1)		
			Coiled spring(s) between cobalt- chromium, titanium-alloy, or ceramic plates embed- ded deep within verte- bral bodies	Modular Intervertebral Prosthetic Disc (IPD)	Dynamic Spine, Inc, San Diego, CA	Predclinical development ⁱⁱⁱ	ATP, ALRP, LTP, via bone window(s) ^{viii}	Complete preser- vation of annulus (transosseous approach)	Potentially highly- invasive, requires 1-2 bone windows, and introduces poten- tial for nonunion

(Y: Yes; N: No; M: Million; ATP: Anterior transperitoneal; ALRP: Anterolateral retroperitoneal; TS: Trans-sacral; LTP: Lateral transpoas; PL: Posterolateral; Post: Posterior).

*CE mark: passed European Conformity (CE) standards; denotes that the product complies with the essential requirements of the relevant European health, safety, and environmental protection legislation.

ⁱDriscoll P. Nucleus Arthroplasty and Nucleus Disc Prostheses in Spine Surgery; Drawn from the Comprehensive Worldwide Spine Surgery Report #M520. MedMarket Diligence. N.p., 14 April, 2012. Web. 28 Dec. 2012.ⁱⁱHydrogels to stem cells: researchers, surgeons revisit disc nucleus replacement. Orthop Today. September 1, 2006.ⁱⁱⁱDi Martino A, Vaccaro AR, Lee JY, et al. Nucleus pulposus replacement: basic science and indications for clinical use. Spine (Phila Pa 1976). 2005;30(16 Suppl):S16-22.^{iv}Ahrens M, Tsantzos A, Donkersloot P, et al. Nucleus replacement with the DASCOR disc arthroplasty device. Spine (Phila Pa 1976). 2009;34(13):1376-84.^vGrad S, Alini M, Eglin D, et al. Cells and biomaterials for intervertebral disc regeneration. Synthesis Lectures on Tissue Engineering. 2010;2(1):50.^{vi}Satellite PEEK Nucleus Replacement Retrospective Analysis. Available from ClinicalTrials.gov. US National Institutes of Health, April 15, 2010. [Accessed December 27, 2012].^{vii}Buttermann GR. Beaubien BP. Biomechanical characterization of an annulus-sparing spinal disc prosthesis. Spine 1. 2009;9(9):744-53.



Figs. 76.1A and B: Example of the DASCOR (Disc Dynamics, Inc, Eden Prairie, MN) injectable liquid, elastomeric nucleus replacement. This device requires percutaneous intradiscal balloon inflation (A) to prepare the implant cavity, followed by injection of the liquid polyurethane implant (B).

Source: From Ahrens M, Tsantizos A, Donkersloot P, et al. Nucleus replacement with the DASCOR Disc Arthroplasty Device. *Spine (Phila Pa 1976)*. 2009;34(13):1376-84.

able substrate has a protein concentration (19%), water content (79%), and various mechanical properties similar to that of the natural disc.²¹ The device is not contained and thus depends on an intact annulus with a minimal annulotomy for implantation.³ NuCore is the first injectable liquid PDR to receive approval by the US FDA under IDE. It is currently being evaluated in the preclinical setting as an adjunct in primary discectomy procedures for subacute disc herniation and for the treatment of DDD.¹⁰

Newcleus (Zimmer Spine, Minneapolis, MN) is also an uncontained device made from polycarbonate urethane. Unlike the other nonhydrogel elastomeric PDRs discussed here, Newcleus is a relatively stiff spacer that coils into its “memorized” spiral shape upon implantation. The implant possesses the unique ability to find its own orientation and position once implanted and thus may not demand the same level of precise intraoperative positioning as required by other precured PDRs and TDRs. Newcleus is apparently under preclinical testing in Europe.

Injectable Liquid Elastomeric PDRs

Hydrogel PDRs can be further divided by their preimplantation form. Products are either initially precured during manufacturing and implanted in a preformed semi-solid

state, or they are manufactured as injectable liquids that solidify in situ. Perhaps the most obvious advantage of the latter is that liquids may be amenable to implantation through a smaller annulotomy and via a variety of minimally invasive approaches. Minimizing the size of the annulotomy may decrease the risk of implant migration following in situ hardening.

Examples of injectable PDRs in development include Biodisc (Cryolife, Kennesaw, GA), an albumin/glutaraldehyde-based hydrogel that cures in situ and DASCOR (Disc Dynamics, Inc, Eden Prairie, MN; Fig. 76.2), a polyurethane-based liquid nonhydrogel. In the DASCOR system, a flexible polyurethane preformed balloon is inserted via small annulotomy into the disc space and filled via catheter with freshly prepared liquid polyurethane until the desirable fill is achieved (Figs. 76.1A and B).²¹ Implanted polyurethane, such as that found in the DASCOR, has been determined to have an elastic modulus ranging from 3.3 to 5.4 MPa, depending on the applied load,¹⁶ and a Poisson’s ratio of 0.48.²² These properties closely resemble those of the native disc. Two-year outcomes for two European multicenter, nonrandomized DASCOR implants in 85 patients demonstrated significant improvement in disability scores, pain scores, and narcotic dependence. No extrusion of devices was noted and only minimal subsidence was noted in two patients.²¹



Fig. 76.2: The Prosthetic Disc Nucleus (PDN; Raymedica, Inc, Bloomington, MN), an elastomeric preformed-solid, hydrogel partial disc replacement. The partial disc replacement consists of a semisolid polymeric core encased in a polyethylene jacket and is shown in its dehydrated (right) and hydrated (left, arrow) states.

Source: From Di Martino A, Vaccaro AR, Lee JY, et al. Nucleus pulposus replacement: basic science and indications for clinical use. *Spine (Phila Pa 1976)*. 2005;30(168):516-22.

Precured Solid Elastomeric PDRs

Precured solid elastomeric devices are preformed implants that are configured to have viscoelastic properties similar to those of the native disc. These are available in both hydrogel and nonhydrogel forms. The major concern with preformed solid elastomeric devices over the course of their history is the potential for extrusion following implantation. This occurs in part because a relatively larger annulotomy is required for implant insertion, which raises the risk of containment failure and device extrusion. Despite these shortcomings, solid elastomeric PDRs are some of the most extensively studied and implanted devices in development.

The Prosthetic Disc Nucleus (PDN; Raymedica, Inc, Bloomington, MN; Fig. 76.2) is the most frequently implanted and most extensively studied PDR to date. Since the original pilot studies in 1996, over 5,500 PDN devices have been implanted.¹⁰ The PDN is composed of a polyacrylonitrile/polyacrylamide core contained in a polyethylene jacket. The jacket is designed to prevent hydrophilic overexpansion in the disc space. Early models of the PDN suffered from problems with implant migration and subsidence, which are thought to have been at least partially addressed through design alterations. This may be second-

dary to the trapezoidal reshaping of the implant, with anterior and posterior wedges that assist in the maintenance of its intervertebral position, as well as modification of its water-imbibing potentials.^{8,19} Although available data from clinical trials indicates good pain relief, improved functionality, and better maintenance disc height in the majority of patients, approximately 10% of these devices have been explanted for migration since their inception.¹⁹

Mechanical PDR Devices

Mechanical PDR devices are designed to maintain the disc space, and are less concerned with replicating the viscoelasticity and annular/endplate interactions when compared with elastomeric PDRs. While mechanical implants are less prone to issues of fatigue, biocompatibility, and potential extrusion or leakage following implantation, they possess some disadvantages, including a relative inability to absorb load, an elevated risk of subsidence, and an inability to evenly disseminate forces across the endplates and annulus.¹⁰

Single-Piece Mechanical PDRs

Several modern single-piece devices are currently under investigation.²³ Regain (Biomet/EBI Medical, Parsippany, NJ) is a disc-shaped biconvex implant with a graphite core and pyrolytic carbon coating (Fig. 76.3). Regain is fashioned from geometric profiles developed via elaborate motion-tracking techniques.⁸ The result is a smooth disc that is designed to conform to the natural concavities of the vertebral endplates. It is available in several geometric anatomic and pathologic (i.e. lordotic) profiles.¹⁹ Similar mechanical interbody spacers under investigation include those composed of polyether ether ketone (PEEK) and cobalt chromium. Clinical data is limited at this time, but clinical trials are thought to be ongoing in Asia.

Multipiece Mechanical PDRs

Partial disc replacement designs employing two or more individual components generally provide an artificial moving articulation between the implant surfaces. This introduces two major design considerations: first, the biomechanics of the artificial articulation and second, the wear profile of the components and potential issues with particle debris. Like TDRs, motion-bearing PDRs can be defined as constrained or unconstrained. Constrained technically refers to the limitation of one or more degrees of freedom (DOF). Several forms of TDR are dual-axis and



Fig. 76.3: Promotional image of Regain lumbar implant (Biomet/EBI Medical, Parsippany, NJ). This single-piece mechanical nucleus replacement consists of a graphite core with a pyrolytic carbon coat.

do permit translation; in these systems, posterior elements such as the facets serve as a block against excessive translation. In these unconstrained systems, supraphysiologic translation may pose risks of increased facet loading and degeneration, or so-called ‘same-segment disease.’²⁴

The NuBac PDR (Pioneer Surgical Technology, Inc, Austin, TX) is a two-piece mechanical PDR consisting of a ball-and-socket joint. It is a constrained device, allowing three degrees of rotational freedom without translation. NuBac features a large surface area that may distribute compressive forces more evenly.¹⁰ It is composed of polyether ether ketone (PEEK), a semicrystalline polymer with high mechanical strength, resistance to wear, and notable biological inertness. Further, its relatively elastic composition is theorized to increase its ability to dissipate compressive forces and therefore decrease risk of subsidence.²⁵ Wear particle debris has been shown to be roughly comparable with other arthroplasties.²⁶ Although preliminary results are encouraging, long-term data from clinical trials is pending.²⁷

The modular Intervertebral Prosthetic Disc (IPD; Dynamic Spine, Inc, San Diego, CA) is a multipiece mechanical PDR, notable for its unconstrained mechanics and potentially annulus-preserving design. The device consists of coiled spring(s) between cobalt-chromium or titanium plates that are embedded and fixed deep within the vertebral bodies (Fig. 76.4). Its spring system permits rotation, as well as translation in axial, coronal, and sagittal

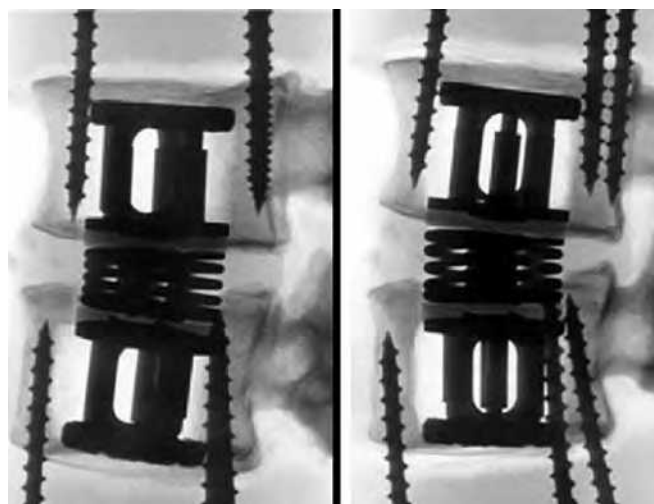


Fig. 76.4: Lateral radiographs of a mechanical multipiece partial nucleus replacement, the Modular Intervertebral Prosthetic Disc (Dynamic Spine, Inc, San Diego, CA). The device pictured is being tested in cadaver vertebrae and is shown in flexion (right) and extension-loaded (left) states. Note that the long screws are not part of the design but are used to hold the vertebrae during pre-clinical testing.

Source: From Buttermann GR, Beaubien BP. Biomechanical characterization of an annulus sparing spinal disc prosthesis. *Spine J.* 2009;9(9):744-53.

planes. With six DOF, the device has the potential, at least theoretically, to better replicate the normal motions of the spine. Furthermore, its modular spring system may allow adjustment of its mechanical properties to better replicate native disc function. Implantation of the device is performed through vertebral bone window(s) and thus leaves the degeneration-prone annulus completely intact.¹² Such potential benefits, however, must be weighed against the morbidities of its relative invasive implantation, given the exposure required for multiple osteotomies, as well as the potentially added risks of iatrogenic injury, postoperative instability, and bone nonunion. The IPD, still in preclinical development, has been inserted successfully into living bovine subjects using various anterior, anterolateral, or direct lateral approaches. Clear benefits of total-annulus preservation in PDRs have yet to be demonstrated.

Operative Indications for Partial Disc (Nucleus) Replacement

Relative indications for disc arthroplasty have included severe, unremitting, and localized lumbar pain at a single

level, 6 months or greater in duration.²⁸ Symptoms must be demonstrated to result from a single, specific degenerated intervertebral space. Facet degeneration and other pathology at that motion segment must be absent and the remaining disc space must be at least 5 mm in height.¹⁰ Positive magnetic resonance imaging (MRI) findings in the setting of LBP do not provide sufficient or reliable indications for arthroplasty. Thus, despite its many controversies, correlative positive discography is considered by many to be a preoperative requirement, as are MRI-visualized Modic changes, consistent with the isolated symptomatic level.

The development of PDR technologies may soon herald a change in indications. Young, healthy patients with single-level early NP degeneration and otherwise healthy spines may benefit from the annulus-preserving potentials of elastomeric PDRs. Such implants might theoretically restore motion, alleviate pain, and actually avoid further degeneration both at the operative and adjacent levels. Additional broader indications proposed for PDRs include otherwise well-preserved discs with recurrent radiculopathy after previous discectomy, or, as discussed, the substitution of diseased nucleus with injectable elastomers during primary discectomy procedures.

Contraindications to Disc Replacement

Absolute Contraindications

Contraindications to TDR/PDR have traditionally been felt to be quite common.²⁹ Absolute contraindications include nondiscogenic pain, lumbar stenosis, active infection or malignancy, skeletal immaturity, morbid obesity [BMI (body mass index) ≥ 40], and known nickel or similar metal allergies. Bilateral spondylolysis, spondylolisthesis, or defects of the posterior elements are also absolute contraindications to PDR. Finally, morbid obesity is contraindicated due to the increased stresses placed across the disc space and the elevated risk of subsidence.

Relative Contraindications

Osteoporosis and osteopenia (T score ≤ -1.0), nonmorbid obesity (BMI 30–40), and the various psychological pathologies comprise common relative contraindications for nucleus replacement. Scoliosis is a debated contraindication, but concern for early loosening and failure exists if devices are placed asymmetrically.

Certain contraindications may exist in relation to the planned surgical approach for the device implantation. Prior intraperitoneal abdominal procedures may have resulted in adhesions that preclude transperitoneal access approach. Some authors warn that prior retroperitoneal procedures are an absolute contraindication to any type of anterior approach, given the potential scarring of, and thus an inability to adequately mobilize, the great vessels.²⁸

Surgical Techniques and Approaches

Total disc replacements and mechanical PDRs are typically performed via an anterior transperitoneal or an anterolateral retroperitoneal approach. Such procedures generally require an anterior approach for direct access to the complete disc space and/or vertebral bodies. Elastomeric PDRs, especially injectable liquid forms, are generally amenable to greater variety of approaches. Like TDRs, specific techniques for implantation vary highly between devices, but share several basic steps, including positioning and approach, annulotomy, removal of the nucleus and endplate preparation, device implantation, and closure.

CONCLUSION

Symptomatic disc degeneration is a common source of LBP and may begin as early as the third decade. Despite its commonality, the diagnosis and management of discogenic pain remains a challenge. Given the nonspecific nature of its clinical presentation and its variable imaging findings, many consider the diagnosis to be one of exclusion. Fortunately, over 90% of patients with nonspecific LBP will typically experience complete resolution of symptoms using conservative measures alone.

For the minority of patients with refractory symptoms, surgical intervention may be indicated. Traditionally, arthrodesis has been the sole surgical treatment option, but its efficacy in this patient population remains poor. Lumbar total disc and nucleus replacement may present attractive alternatives because of their theoretical abilities to eliminate pain, prevent or slow adjacent segment disease, and restore the natural kinematics of the spine. Total disc replacement has been performed for over 20 years internationally with varying success rates, and has shown equivalence to fusion for symptomatic patients in some FDA trials.

Partial disc replacement, a type of arthroplasty that replaces the NP but spares the annulus portions of the

disc, is in its infancy. At this time of publication, no devices are cleared for routine use. However, investigational trials, both domestically and internationally, have demonstrated some preliminary success. Partial disc replacements have the potential to combine the motion-sparing benefits of TDRs with the ability to preemptively treat the source of early-stage disc degeneration, the nucleus. Early restoration of nuclear function is thought to promote healthy interaction with the annulus and the surrounding endplates, and potentially halt the degenerative cascade.

KEY POINTS

- Discogenic pain is a common source of lumbago; 90% of cases will resolve with nonoperative measures alone.
- Symptomatic disc degeneration is a diagnosis of exclusion.
- Fusion remains the standard surgical treatment for discogenic pain despite controversial indications and poor outcomes in this population.
- In select patients, lumbar disc arthroplasty may be an effective alternative to fusion. Precise indications include isolated, single-level, degenerative disc disease with an absence of facet, or adjacent degenerative processes. Symptoms must be refractory to nonoperative measures and 6 months or longer in duration.
- Partial disc arthroplasty may be indicated for patients with isolated disease of the nucleus pulposus. Many of the proposed techniques may be performed in a minimally invasive manner and have the theoretical potential to eliminate axial pain, restore disc height and motion, and protect the surrounding annulus from further degeneration.
- At the time of publication, all partial disc replacement devices are for investigational use only.

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Annular Disease and Surgical Treatment of the Annulus

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Snapshot

- » Annular Pathology as the Target of Therapy
- » Clinical Assessment and Diagnosis

- » Case Example

ANNULAR PATHOLOGY AS THE TARGET OF THERAPY

According to a cadaver study conducted by Kirkaldy-Willis in the 1970s, the disc undergoes degenerative changes involving a cascade of events leading to reduced segmental stability followed by a natural stiffening of the segment.¹ Early changes, namely annular tears, are often neglected which leads to a limit of the understanding of symptom generation, an overemphasis on imaging, and inadequate treatment plans. Kirkaldy-Willis has since elaborated on nerve root and pain generation noting that a degenerative disc may present with back pain, sciatica, and claudication without impinging on nerve roots.² Although surgeons have historically managed symptoms of neural compression or spinal instability, they traditionally have not addressed early annular pathology. Recently, there has been a growing interest in addressing annular defects earlier on to address symptoms and limit the progression of the degenerative process. Utilizing various technologies through a transforaminal endoscopic approach under local anesthesia has allowed surgeon to better understand and address annular disease. A typical case is shown in Figure 77.1 where a posterolateral annular tear resulting in a herniated can be seen in a patient complaining of severe low back and leg pain.

Structure and Function

Intervertebral discs are composed of two primary structures: an outer annulus fibrosus that surrounds an inner

nucleus pulposus.³ The annulus fibrosus is well-organized into a series of concentric laminar fibrous rings. The rings are separated by interlamellar septae which contain an adhesive complex made of proteoglycans. The cohesiveness between the rings allows them to work in unison while dynamic loading forces are applied. The annulus is made of type I collagen, proteoglycans, water, and fibroblast-like cells. The collagen fibrils resist tensile and distraction forces, while the fibroblast-like cells are responsible for making type I collagen and proteoglycans. In addition, the annulus fibrosus can be further divided into an inner and outer portion based on structural differences. The inner annulus

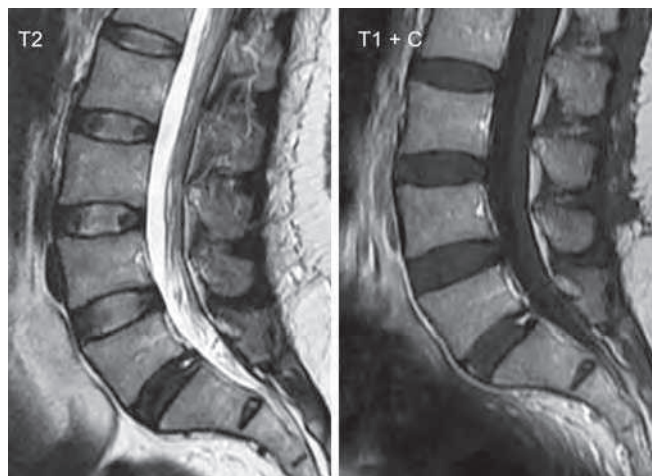


Fig. 77.1: MRI of L5-S1 intervertebral disc with a posterior annular tear with associated degenerative changes, but no cord compression in patient who presented with back and leg pain.

fibrosus is a transition zone between the outer annulus and the central nucleus pulposus. The inner annulus contains an extracellular matrix that is a hybrid of both: containing less organized, compact rings than the outer annulus, but remaining less hydrated than the nucleus pulposus. The nucleus pulposus is made of type II collagen, proteoglycan, water, and chondrocyte-like cells. It is able to resist compression well due to the higher proteoglycan and water content. The viscoelastic matrix helps to equally distribute forces and the chondrocyte-like cells make type II collagen and proteoglycans. The intervertebral disc is avascular with most of its nutrition reaching the nucleus pulposus through diffusion. The sinuvertebral nerve which arises from the dorsal root ganglion innervates only the superficial fibers of the annulus. However, an ingrowth of nerve fibers into deeper layers of the annulus has been observed in degenerative disc.⁴

Types of Annular Tears

There are three main types of annular tears: peripheral, concentric, and radial (Fig. 77.2). A peripheral tear, also known as a rim tear, involves the most peripheral lamellae of the annulus. A concentric tear is circumferential and splits between the lamellae of the disc. Both peripheral and concentric tears tend to occur as a result of an acute traumatic event, such as during sporting activities. However, radial tears, which progress from the innermost part of the annulus to the outer margins, are commonly a result of degenerative changes. Tears near the junction between the cranial endplate and annulus lead to an upward migration of herniated nuclear fragments as opposed to a downward migration when the tear is closer to the caudal endplate. The propagation of annular tears can result in extrusion of the nucleus pulposus into the annulus with

concomitant leakage of proteins and cytokines into the disc space and surrounding soft tissues and nerves.

Hypothesis of Symptom Generation

It is thought that symptoms from an annular tear emanate from the ingrowth of vascular tissue and nerve endings into the annulus with the associated presence of inflammatory cytokines and chemokines that are produced by the degenerating intervertebral disc (IVD). When exploring the annular tear surgically in a patient with severe back pain, it is common for the surgeon to encounter incarcerated fragments of the nucleus pulposus with the inflamed annular tissue. It has been hypothesized that these fragments may prevent healing of the defect and lead to chronic pain and disability.⁵

Pathophysiology

Following an annular tear, there is an ingrowth of vascular tissue and dense nerve fibers into the annulus, which become inflamed from the release of cytokines.⁴ The annulus has poor intrinsic healing capability which is further limited by the entrapped nucleus pulposus fragments. The tear is unable to seal off due to the herniated fragments, resulting in persistent leakage of cytokines.⁵ Other pathological changes also occur during aging. The number of layers in the annulus decrease with age, which is compensated by an increase in thickness of the remaining layers.⁶

Neurologic symptoms and pain associated with an annular tear are mediated mostly by cytokines and a cascade of inflammatory changes as opposed to mechanical compression associated with a herniated disc.^{7,8} The cytokines induce an up regulation in sodium channels in nerve endings which play a role in radiculopathy and can be blocked with local anesthetics that target

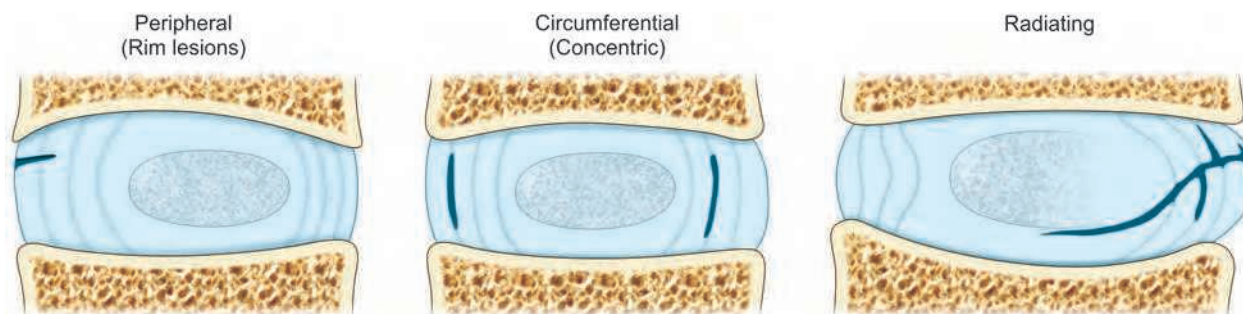


Fig. 77.2: The three types of annular tears are peripheral, circumferential, and radial tears (left to right).

peripheral sodium channels.^{9,10} This is further supported by the mitigation of nucleus pulposus-induced effects on nerve conduction velocity by cytokine inhibitors.¹¹

The normal intervertebral disc is poorly innervated with nociceptive nerve fibers only penetrating a few millimeters into the annulus. However, with degenerative changes the annulus becomes more friable and cytokines induce vascular and neural growth. Substance P and other cytokines have also been found extensively in nerve fibers along the margins of the annulus.^{12,13} Neurotrophins, which induce neural genesis, survival, and development, also play a role in the symptomatology of annular tears. Neurotrophins alter the extracellular matrix, increase the density and distribution of nerve fibers, and induce the production of others proinflammatory cytokines.¹⁴ These changes result in further nerve ingrowth into the intervertebral disc, synthesis of pain-related peptides, and transmission enhancement of pain signals in the dorsal horn of the spinal cord.^{14,15} Pain is then transmitted through a rich nerve plexus that surrounds the outer surface of the degenerative annulus. The nerve plexus is made up of the meningeal branches of the sinuvertebral nerves that enter the spinal canal through the neural foramen and bifurcate into ascending and descending branches.

CLINICAL ASSESSMENT AND DIAGNOSIS

The typical patient with a symptomatic annular tear will present with axial back pain with or without leg pain radiation. The location and intensity of the pain will vary from patient to patient. The author has found that extension posture according to the technique demonstrated by McKenzie is useful in the diagnostic process. If the patient experiences centralization of pain with this maneuver, it is more likely that the annulus is intact. On the other hand, a patient who does not achieve centralization with the maneuver is more likely to have annular disruption requiring intervention.^{15,16}

For patients with leg pain, there is generally good correlation between the side of the annular tear on MRI and the side of radicular leg pain. In some cases, EMG can be useful to correlate the level of the nerve root irritation.^{17,18}

The straight leg raising test is generally normal in cases of symptomatic annular tear with back or leg pain as the root is adequately mobile in the foramen. Alternatively, the Gore sign may be useful in detecting and confirming inflammatory involvement of the nerve root in

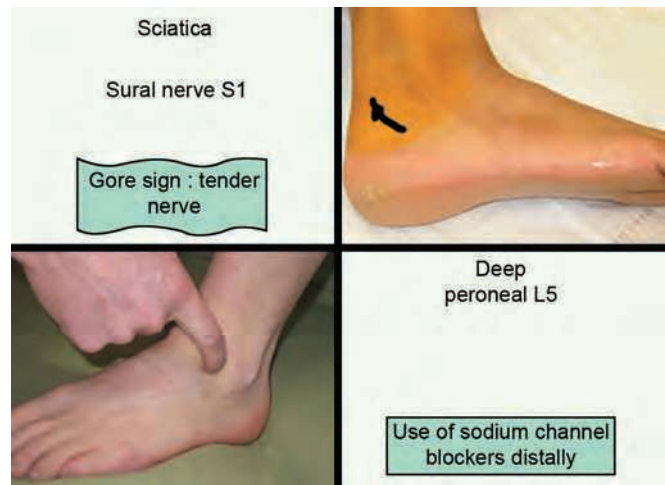


Fig. 77.3: The Gore sign can be elicited by palpating the deep peroneal or sural nerve over the lateral aspect of the ankle as demonstrated above.

sciatica associated with annular tears. To perform this test, the examiner palpates the inflamed symptomatic nerve rather than just depend on pain distribution and dermatomal understanding or enhanced MRI to diagnose the radicular involvement.¹⁹ Specifically, the Gore sign can be performed by palpating the lateral terminal branch of the deep peroneal nerve to assess L5 involvement and by palpating the sural nerve to assess S1 symptoms (Fig. 77.3).

Imaging

Plain radiographs are only able to identify the changes associated with the later stages of the degenerative cascade such as disc space narrowing, osteophyte formation, and segmental deformity. They are therefore not helpful for early stage interventions. MRI with T2-weighted imaging is, however, able to show dehydration, blurring of the annulus/nucleus junction, and bright signal within the annulus at the sight of a high intensity zone (HIZ). HIZ may be correlated with a positive response to provocative discography and may be a marker for discogenic pain. However, an HIZ can also be seen in some asymptomatic patients.

Annular tears are also evident on gadolinium enhanced T1 weighted imaging which can be used to demonstrate the vascularized granulation tissue within the margins of the annulus.^{20,21} In some cases, pooling of gadolinium may be observed around symptomatic annular tears, suggestive of neovascularization and inflammation due to a leakage of cytokines from the disc via the annular tear.²²

When assessing the MRI studies, it is important to ensure that the disc remains contained, if an annular repair procedure is to be planned. In particular, the posterior and posterolateral annulus should be carefully studied as this region has been shown to be the primary symptom generator.

Discography

Discography (Fig. 77.4) is a potentially useful tool when assessing a patient with severe axial back pain thought to be of annular origin. Discography can demonstrate the morphologic characteristics and integrity of the disc, as well as the location and size of the tear. With current techniques, discography is more accurate than MRI for the detection of annular pathology as a normal MRI does not exclude structural disruption of the annulus.²³⁻²⁵

Transforaminal Endoscopy

Transforaminal endoscopy provides a powerful tool to assess the annulus for pathologic involvement as the tissue integrity, presence of nuclear material, and inflammatory tissue in the region of the defect can be directly observed. Transforaminal endoscopy under local anesthesia has begun to replace other invasive studies, such as provocative discography in the practice of some experts in the field.



Fig. 77.4: Discography—lateral film of L5-S1 intervertebral disc demonstrating contrast leaking out into the epidural space through an annular tear.

Operative Planning

Anatomy of the Target Area

The disc height must be assessed preoperatively and should be sufficient to allow entry and free movement of the endoscope within the disc space. The posterior annulus can be conceptually represented by a rectangle bound by upper and lower endplates at the level of the disc, and the borders of the pedicle on both sides in a coronal or AP image. Normal interpedicular distance varies from 24 to 36 mm as one descends from the L1 to the S1 level.

With a unilateral transforaminal approach, the annulus from the entry site in Kambin's triangle to midline may be accessed. If the tear is more extensive than what can be addressed with a unilateral approach, bilateral biportal access must be considered.

Using transforaminal access, area of an annular tear can be debrided and then treated with thermal energy to create shrinkage and closure of the torn tissue. This type of annuloplasty can also be performed from inside the disc, avoiding the formation of epidural scar tissue within the spinal canal.

Transforaminal Surgery

The patient is positioned prone on a radiolucent table. Using the image intensifier, the bony landmarks are marked out on the skin. This includes the midline, disc space and medial borders of the pedicles. Using lateral fluoroscopy, the inclination angle of each disc space is also demarcated. The entry for access to a given disc is at the intersection of AP and lateral lines, approximately 10–12 cm lateral to the midline.

Access to L5/S1 level is generally through the same skin incision as the L4/L5 level. Due to the inclination of the disc and the presence of the iliac crest it is mandatory to go above the crest. After making a small 8 mm skin incision, a 25 cm long spinal needle is used to establish the trajectory to the disc space, after which local anesthesia is injected along this tract—including the sensitive area of the ipsilateral annulus. The angle of the needle is generally about 25–30° above the horizontal plane in a prone patient. The needle tip extends into the foramen and docks on the annulus at the level of the medial pedicle.

After establishing and anesthetizing the tract to the annulus, the dilator is inserted (at the same angle), followed by the endoscopic cannula which is docked bluntly against the margin of the disc. Using a 25° endoscope,

inspection of the annulus and foramen can be carried out. At this stage, it is common to observe the presence of disc fragments in annular defects and vascular granulation tissue along the margins of the annular tear. Using probes, the tissue can be assessed, and fragments of nucleus are mobilized and removed. All loose nuclear material within the annular defect is removed prior to treating the area with radiofrequency or laser energy to shrink the tissue and close the tear. Prior to withdrawal of the endoscope, the traversing and exiting nerve roots are inspected and mobilized as the endoscope is withdrawn to the annular surface.

CASE EXAMPLE

The sagittal MRI of a patient with chronic lumbar discogenic pain demonstrates a radial annular tear at the L5-S1 level. Due to the severity of symptoms, the patient was offered transforaminal endoscopic treatment. During surgery, the posterolateral annulus was examined. At the beginning of the procedure, the nucleus pulposus was injected with indigo carmine stain. During endoscopy, the blue color of the nucleus was seen along with red granulation tissue. The nucleus tissue was debrided revealing the annular tear and granulation tissue adjacent to the tear. The annular tear was then treated with electrothermal annuloplasty (Fig. 77.5).

Aftercare

The use of an orthosis postoperative is not routinely recommended. Basic activities of daily living can be

initiated as tolerated at the time of discharge. Activity restrictions can be lifted at 4–6 weeks following surgery at which point physical therapy that focuses on core strengthening and stability can be initiated. The typical course of healing may vary depending on the thickness of annular tear, but it generally occurs over 3–6 months.

Complications

Complications can include as nerve root injury, spinal cord injury, infection, epidural abscess, discitis, and scar tissue formation. The use of laser and RF probes near the nerve and dorsal root ganglion can result in dysesthesias, which are usually self-limiting and subside within 4–6 weeks. More severe dysesthesia can also be treated with foraminal epidural blocks or with oral gabapentin.

Outcome

The literature support for the treatment of annular tears is variable depending on the mode of treatment. Due to high association of annular tears with other lumbar pathology, the indications for treatment of many of the clinical trials includes chronic discogenic pain which in part is attributed to annular tears.

Primary closure of annular tears with suture has largely been limited to biomechanical and animal studies. Suture repair has been shown to restore the mechanical integrity of the annulus fibrosus.²⁶ Also, in a porcine model, suture repair demonstrated reduced inflammatory changes over time and slower progression of disc degeneration compared to no repair of annular defect.²⁷

Other alternative includes intradiscal electrothermal therapy (IDET) and intradiscal radiofrequency thermocoagulation (IRFT). The proposed mechanism for these types of annuloplasty is ablation of nociceptors and shrinkage of collagen fibers to stiffen the IVD. In a prospective case series comparing IDET and lumbar fusion surgery, the IDET group showed a statistically significant and clinically meaningful improvement in pain and functional outcomes at a minimum follow-up of one year.²⁸ Similarly in a case-control study, almost 90% had a statistically significant improvement in pain scores and all patients in the treatment group returned to work.²⁹ In contrast, in the control group, which underwent a physical rehabilitation program, only one patient had a significant improvement of pain and more than half of the 17 patients had worsening pain. Only 20% of the control group returned to work.

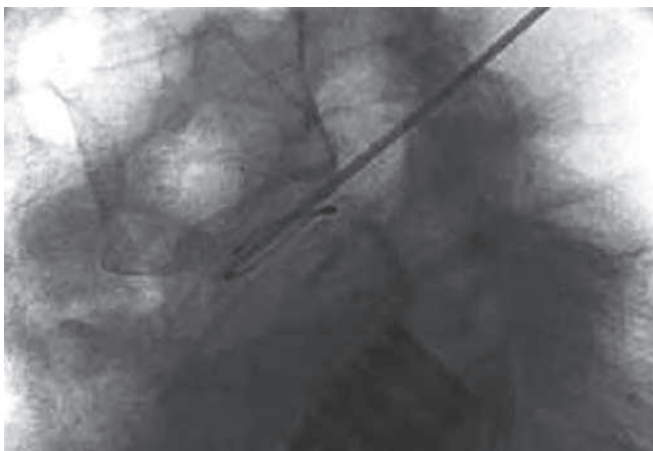


Fig. 77.5: Intradiscal electrothermal therapy (IDET)—intraoperative fluoroscopy of L5-S1 demonstrating catheter placement for IDET in the posterior annular wall.

One of the main concerns with annuloplasty is the potential for accelerated degeneration of the IVD. However, the efficacy of IDET is not uniformly supported. Freeman et al. conducted a randomized, double-blind controlled trial that IDET resulted in no improvement in functional outcomes at 6 months compared to baseline and the control group.³⁰ The current body of evidence for IRFT is limited with a small randomized double-blind study indicating that RF thermocoagulation is no more effective than placebo at eight weeks.³¹

The different types of annuloplasty are designed to approximate or reduce the size of the tear which prevents the nucleus pulposus from herniating and limits the ongoing inflammatory response. However, annuloplasty fails to restore damaged fibers and promote healing. Therefore, the search for biological treatments that enhance regeneration have been proposed. Biological treatments mainly consist of direct injection of regenerative substances, gene therapy, and tissue engineering. However, most biologic treatments have been restricted to in vitro and animal studies. Recently, platelet-rich plasma (PRP) has received more attention and has even been evaluated in human clinical trials demonstrating a potential role in intervertebral disc pathology. In one prospective, double-blind, randomized controlled trial, intradiscal autologous PRP resulted in better pain control, patient satisfaction, and functional outcomes.³² The readily available source of autologous multipotent stem cells from PRP and its supported use in other areas of orthopedics has made it an attractive option, but larger studies are still required.

SUMMARY

Annular tears occur as part of the degenerative process of the intervertebral discs. The most important tears from a clinical perspective are radial in nature, affecting the peripheral region of the annulus. Following the formation of an annular tear, the body may react with neovascularization and neurotization along the outer margins of the disc, eventually leading to symptoms of back pain or chemical irritation of nerve roots—potentially leading to sciatica. Annular tears can be detected by MRI or discography. Annular tears presenting as back pain can be treated by debridement followed by thermal or light ablation with shrinkage of the torn annulus. Annular defects which contain herniated nuclear material can be treated by transforaminal excision of the herniated material followed by approximation of the

annular defect by annuloplasty. The results of endoscopic treatment of selected annular defects appear promising, but are still limited small clinical trials and so large, prospective studies are needed to demonstrated the efficacy and long-term outcomes.

KEY POINTS

The annulus acts like a barrier between the nuclear tissue and the nerve fibers. Normal function of the spine requires integrity of the annulus. An annular tear may lead to back or leg pain. Surgical techniques to restore the annulus are being developed.

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Surgical Management of Lumbar Degenerative Disc Disease

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Snapshot

- » Diagnostic Workup
- » Nonoperative Management
- » Surgical Treatment
- » MIS PLIF/TLIF
- » XLIF/DLIF

INTRODUCTION

Axial low back pain can be a disabling disease to a large percentage of the population. Over 90% of the United States population will suffer from back pain at some point in their lives, making nonoperative management of physical therapy, cognitive and behavioral therapy, and anti-inflammatory medications the mainstay of treatment. When back pain is unremitting and cannot be managed successfully with conservative care, surgical intervention can be discussed. Even then only a specific patient population may benefit. In order to provide cost-effective health care and consistent postoperative outcomes, spine surgeons must exercise selective indications.

DIAGNOSTIC WORKUP

Standard workup for low back pain includes obtaining anteroposterior (AP), lateral, and flexion–extension lumbar radiographs. These films should be scrutinized for findings suggestive of degenerative disc disease such as osteophyte formation, endplate sclerosis, facet arthrosis, and calcification of the intervertebral disc. Keeping the possibility for surgical intervention in mind, the lateral image can be studied for calcification of the great vessels in case an anterior approach is employed to reach the level of the intervertebral disc. Other degenerative pathologies such as degenerative or isthmic spondylolisthesis should be ruled out, in particular with flexion–extension films,

by screening for subtle translation of the vertebral bodies. Transitional anatomy and the level of the crest with respect to the involved intervertebral level should be noted for surgical planning.

Magnetic resonance imaging (MRI) is the standard of care to accurately assess the status of the intervertebral disc. More obvious findings include disc desiccation (commonly referred to as “dark nucleus” due to the loss of the hydration signal on the T2 sequence), high intensity zones in the posterior annulus (indicating a tear through which disc material can potentially herniate), Modic changes in the vertebral body endplates surrounding the disc, and collapse of disc height associated with bulging or herniation of the disc (Fig. 78.1). Modic changes are described by three stages¹: In stage 1, there is decreased T1 signal in the endplate and increased T2 signal thought to be associated with disruption and fissuring of the endplates and the presence of vascularized fibrous tissue ingrowth or edema. In stage 2, there is increased signal in the endplate on T1 and isointense signal in T2, associated with yellow marrow replacement or deposition of fat. Modic stage 3 changes are indicative of advanced degenerative changes such as endplate sclerosis, and the signal on both T1 and T2 is decreased within the endplate. In addition to disc changes on MRI, signs of facet degeneration or arthrosis may be present including facet hypertrophy (resulting in encroachment on the central canal and spinal stenosis) or loss of articular cartilage.



Fig. 78.1: Degenerative disc disease: Classic findings on this sagittal T2-weighted image include desiccated disc, loss of height, disc bulging, Modic changes in the vertebral endplates.

In the setting of back pain, it is simple to identify the potential source of pain in those patients whose MRI demonstrates a single level of involvement. On the other hand, when there is a spectrum of findings at multiple levels, the source is more difficult to elucidate. Since surgical morbidity and success rate of treatment follow opposing trends as the number of levels operated on increases,² it is important to attempt to identify which disc is the most likely pain generator. Boden et al. performed MRIs on 67 asymptomatic individuals and found that the approximately 33% of them had substantial abnormality.³ Of those older than the age of 60 years, 57% had an abnormality and this incidence significantly increased to almost 100% in those aged 80 years. Borenstein et al. performed a 7-year follow-up on these patients and demonstrated that findings of degenerative disc disease on MRI were not predictive of development of low back pain or duration of related symptoms.⁴ This would imply that despite findings of degenerative disc disease at multiple levels, all of those levels may not necessarily be responsible for a patient's symptoms.

Discography is a diagnostic tool that is believed to help ascertain whether a disc that has radiologic signs of degeneration is responsible for clinical symptoms. Under fluoroscopic guidance, a needle is inserted into the targeted disc. The opening pressure is then measured using a manometer. A specific volume of fluid is then injected into the disc while making continuous pressure recordings with an upper limit of pressure measured set, at which the test

will be aborted. As the disc is injected, the patient is asked to determine whether they experience pain secondary to this procedure similar in character to their usual low back pain. If this is the case, the discogram is determined to be concordant, and the pressure at which the symptoms are generated is recorded. If the pressure limit is reached without recreation of symptoms, the discogram is determined to be nonconcordant.⁵ The use of discography, however, is controversial. Carragee et al. performed a prospective match-controlled study of disc degeneration over 10 years with and without baseline discography.⁶ Those discs that had been exposed to puncture and injection had progression of disc degeneration at a 35% incidence in the discography group compared with 14% in the control group. New disc herniations were disproportionately found on the side of the annular puncture, and there was a significant difference found in measurements of disc height and disc signal intensity in the two groups. This alarmed the spine community to the potential hazards of diagnostic testing with discography as it is often the case that a control disc with minimal signs of degeneration is injected in addition to the degenerative disc to add validity to the test results. Carragee et al. as well as multiple other groups have studied the false-positive rate of discography and have found results as high as 25%, with accuracy of the test diminishing in the presence of psychosocial history or chronic pain syndromes.⁷⁻¹⁰ Other critics of the tool also emphasize that the result is based on a subjective patient response and therefore can be subject to significant confounding bias. Thus, the surgeon must be wary in use of discography as an adjunct to surgical planning in those with degenerative disc disease and chronic low back pain.

■ NONOPERATIVE MANAGEMENT

There is a wide breadth of nonoperative modalities that are available to patients with disabling chronic low back pain. Prior to arriving at a surgical discussion, all reasonable options should be exhausted. There is a significant body of literature that exists on various means to approach back pain. Mainstays of treatment include activity modification, use of nonsteroidal anti-inflammatory medications with special attention to any conflicting comorbidities, and physical therapy that emphasizes core strengthening. More recently, studies have included a focus on cognitive behavior therapy as part of the physical therapy. Brox et al. performed a randomized study on lumbar fusion versus cognitive intervention and exercise, and found equal improvements in patients with chronic low back pain to

those treated with lumbar fusion.¹¹ There are multiple alternative therapies that are available to patients as well including treatment by a chiropractor or acupuncturist. Though the literature does not yet validate the use of these modalities, patients often report symptomatic relief.

SURGICAL TREATMENT

Candidates for surgical intervention include patients with chronic disabling low back pain that have trialed various nonoperative modalities and have signs of degenerative disc disease on imaging studies. Careful selection of patients including assessment of psychosocial factors, medical comorbidities, and functional reserve is critical to achieving optimal outcomes.

Prior to the advent of motion sparing technologies, the most common surgical treatment for chronic axial back pain in the appropriately selected patient was lumbar fusion. Prior to the use of instrumentation, this was accomplished with a posterolateral fusion between the transverse processes. At present, there are multiple methods to accomplish a lumbar fusion and these may or may not include pedicle instrumentation as well as an interbody fusion.

The goal of any fusion, regardless of technique, is to eliminate motion in the lumbar motion segment. Previously it was thought that motion at the lumbar spinal unit was responsible for the pain. In degenerative disc disease, the disc is thought to be the pain generator. Therefore, the goal of the fusion in this setting is to eliminate motion while also removing the disc. The approach to the disc is the main differentiating factor between techniques that have been developed to obtain an interbody fusion.

Posterolateral Fusion

Before the implementation of instrumentation, fusions were obtained in the posterolateral bed between the transverse processes. A midline lumbar skin incision was made and used to expose the midline elements, the posterior facet capsules and joints, and the transverse processes of the levels to be fused. Care is taken to preserve the facet capsule of the cephalad level, and decortication of the index facet, pars, and transverse processes of the levels to be fused is performed. The goal is to stimulate bony bleeding and thus deliver osteogenic cells to the fusion bed. Various bone substitutes that are both osteoinductive and osteoconductive can then be added to the fusion bed and allow for a bony mass to form in this area to create a stabilizing effect between the two functional spine units. The

main concern about treating degenerative disc disease with a posterolateral fusion alone is the potential for pseudoarthrosis and thus continued motion at this level resulting in persistence of pain symptoms. However, for a single level noninstrumented fusion in the setting of degenerative disc disease, McCulloch has reported a 91% fusion rate with successful clinical outcomes.¹²

Instrumentation in the form of pedicle screw-plate systems and pedicle screw-rod systems afforded semirigid and rigid constructs, respectively. Theoretically, these constructs maintain temporary fixation while bone is generated in the posterolateral fusion bed. Whether or not these systems improved fusion rates and, moreover, clinical outcomes is debated throughout the literature. Though this topic has been the focus of multiple studies, the various diagnoses included in those who underwent fusion by these systems makes it difficult to discern whether instrumentation truly improves fusion rate and clinical outcomes. France et al. demonstrated a fusion rate of 76% versus 64% in instrumented versus uninstrumented fusions with the use of variable screw placement (VSP), a semirigid system.¹³ Their population included patients with degenerative spondylolisthesis as well as degenerative disc disease. Importantly, they showed no statistically significant difference in clinical outcome scores. On the other hand, Lorenz et al. compared a single-level fusion with VSP versus uninstrumented fusions and found statistically significant differences in fusion rates, pain improvement scores, and return to work between the two groups.¹⁴ Their patient population included only those patients with chronic disabling discogenic pain for >6 months. Zdeblick et al. also demonstrated >90% fusion rates and outcome success with rigidly instrumented fusions when compared with semirigid fusion and posterolateral fusion alone.¹⁵ Thomsen et al. conducted a randomized prospective study in which they were unable to demonstrate sufficient benefit from instrumentation in either fusion rate or clinical outcome over those who did not receive instrumentation.¹⁶ Both groups had a high rate of fusion and successful outcomes. Given the significant risks associated with instrumentation including potential nerve root damage from aberrant screw trajectories, they warned against routine use of pedicle instrumentation in adjunct with posterolateral fusions.

Interbody Fusion

As mentioned above, an additional surface across which a fusion can be obtained is the vertebral endplate. This is

termed an interbody fusion. There are multiple methods to approach the intervertebral space with the common goal of removing the pathologic disc and obtaining a bony bridge between the vertebral bodies. As opposed to the tension forces that are present between the transverse processes posteriorly in the erect position, compressive forces are present anteriorly between the vertebral bodies. This, in combination with the large surface area of the endplate, leads to a higher chance of successful fusion. Studies have focused on whether clinical outcomes are improved with interbody fusion as, theoretically, removal of the disc itself directly addresses the pain generator in degenerative disc disease. In addition, biomechanical studies such as those by Lee and Langrana have shown that while posterolateral fusions can increase axial stiffness by 40%, anterior interbody fusions can increase this same parameter by as much as 80%.¹⁷ The greater the stabilization at a given motion segment, the greater the theoretical pain relief. Barrick et al. found that patients experienced pain relief with anterior lumbar interbody fusion (ALIF) after prior posterolateral fusion had been performed.¹⁸ Weatherley et al. had similar results of pain relief in five patients who despite showing a solid posterolateral fusion had significant pain and subsequent pain relief with performance of an ALIF.¹⁹ More recently, however, Høy et al. have documented that patients with degenerative disorders did not significantly do better with a transforaminal lumbar interbody fusion (TLIF) when compared with posterolateral instrumented fusion.²⁰ Whether this is attributable to the type of interbody cage, placement of the cage, lordosis gained, or other clinical parameters, is a subject of debate. Much like the controversy that exists with instrumentation, further studies would be needed to delineate whether an interbody fusion is universally superior to a posterolateral instrumented fusion.

Anterior Lumbar Interbody Fusion

The first described interbody fusion was performed via an anterior approach in the 1930s. Burns described this operation as a treatment option for a diagnosis of spondylolisthesis.²¹ In the 1970s, Crock described a disorder termed internal disc disruption occurring after intervertebral disc lesions (i.e. herniations) and his treatment by ALIF.²² Today, there are a multitude of methods by which ALIF can be accomplished with the use of bone grafting, various cage devices, and advanced osteobiologics. The anterior approach is performed either by a longitudinal

incision, especially in the case of multilevel interbody fusion for access to multiple levels and adequate exposure, or by a low-lying transverse abdominal incision. In most cases, the surgeon gaining access will dissect lateral to the rectus abdominis and then proceed either in a transperitoneal or retroperitoneal fashion to reach the aorta and inferior vena cava overlying the anterior disc spaces. Careful dissection must be performed of the vessels away from the anterior longitudinal ligament, and specialized retractors are used to maintain their position and access the disc space to perform the interbody fusion.

Retrograde ejaculation (RE) is a potential complication associated with the anterior approach that can occur as the parasympathetic plexus is dissected through or swept away from the field in order to gain access to the disc space. Sasso et al. have reported a higher incidence of RE in a single-level anterior interbody fusion with a transperitoneal approach (13.3%) as opposed to the retroperitoneal approach (1.7%).²³ At 2-year follow-up in their cohort of patients, 10% and 0.86% of patients had permanent RE in these respective groups. In the past decade, much research has focused on the increased incidence of RE with the use of recombinant human BMP-2 (rhBMP-2) as an osteogenic supplement to the ALIF. Though this concern was identified in initial Food and Drug Administration (FDA) trials with rhBMP-2, the true incidence of RE remains debated. Carragee et al. performed a retrospective analysis in which they identified RE in 7.2% of two-level ALIF patients in whom rhBMP-2 was used versus 0.6% of those patients in whom the synthetic recombinant protein was not used.²⁴ When assessing single-level ALIFs, there was a 6.7% rate of RE in those who received rhBMP-2 versus 0% in those patients who did not. Burkus et al. pooled the data from five different prospective randomized multicenter FDA Investigational Device Exemption (IDE) trials.²⁵ With their combined population, they found that 3.4% of those in whom rhBMP-2 was used developed RE versus 1.7% in those in whom it was not used. This difference was not statistically significant, however. They also confirmed a much higher incidence of RE with a transperitoneal approach of 8.6% versus 1.6% with the retroperitoneal approach. Recently, Tepper et al. have highlighted that the mechanism by which RE is reported may play a critical role in determining the true incidence of the complication.²⁶ This group showed that the typical questionnaire used to report RE may overestimate the incidence. In fact, when using quantitative semen and urine analysis, the incidence of RE found in comparative cohorts with and without the use of

rhBMP-2 for ALIF was almost identical at approximately 10%. Regardless, the preoperative discussion held with a patient regarding potential for sterility from the anterior approach is an important part of the decision to pursue surgical intervention.

Once the targeted disc space has been exposed via an anterior approach, an annulotomy is performed and the entirety of the disc is removed. The cartilage from the endplates is removed to reach bleeding subchondral bone. The disc height and space are then restored with some combination of autograft, allograft, osteobiologics, and/or an intervertebral cage device. In the earlier attempts at anterior interbody fusion, various forms of autograft were used. The first described was an autologous tibial peg. More commonly, prior to the advent of cages if autograft was used it was in the form of a tricortical iliac crest autograft. Over time, the interbody has evolved to a cage design packed with some form of bone or osteobiologic, as the cage is designed to temporarily stabilize the interspace as the bone bridge is formed between the endplates. Dennis et al. showed that in fact there can be loss of disc height over time as fusion is achieved and therefore it is important for the cage to be able to withstand physiologic mechanical loads during the incorporation process.²⁷

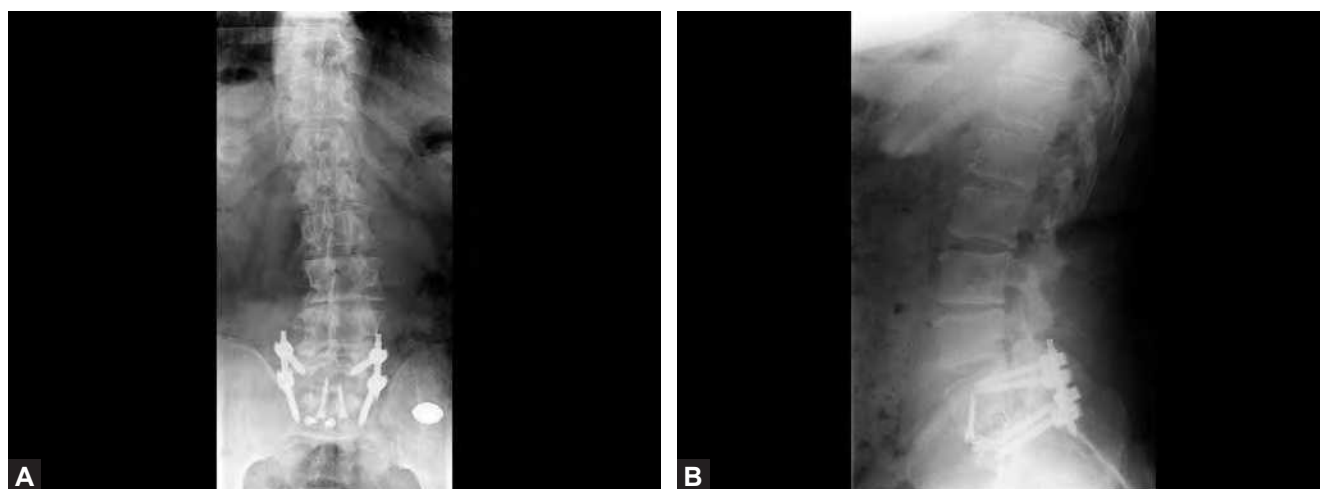
The initial attempts at interbody fusion from an anterior approach were by implantation of material into the disc space to allow for a fusion without the addition of supplemental instrumentation. This is termed a “stand-alone ALIF.” The quoted rates of fusion for treatment of symptomatic degenerative disc disease with an ALIF are variable. Chow reported on 97 patients treated with autogenous corticocancellous bone graft and had a fusion rate of approximately 63%.²⁸ Loguidice et al. treated 85 patients with either autograft (tricortical or dowel) or allograft and had a cumulative fusion rate of 75%.²⁹ Blumenthal documented a similar rate of 73%.³⁰ Newman and Grinstead had a much higher success rate at 89%, demonstrating fusion with lack of motion of flexion-extension radiographs.³¹ With the introduction of threaded cylindrical cages, the rate of fusion for ALIF was consistently elevated above 90%. Kuslich and Bagby published a single-level fusion rate of 98% in an FDA effectiveness trial while two levels had a fusion rate of 80% with the use of BAK (Bagby and Kuslich; Spine-Tech, Minne Polis, MN) cages composed of titanium.³² Sasso et al. found a 60% fusion rate in a control arm treated with a femoral ring allograft packed with autograft bone, while their experimental arm treated with a cylindrical titanium

cage packed with autograft had a 97% radiographic fusion rate at 2 years follow-up.³³ Thus, the quoted rate of anterior fusion varies from approximately 60% to 90% in the literature.

Advantages of the anterior approach include the ability to restore disc height, lordosis, and foraminal patency. In addition, the need for posterior spinal musculature dissection and healing is obviated. Complications associated with pedicle screw placement are also avoided. The majority of complications and thus disadvantages associated with the anterior approach are a result of the approach itself. As a result of manipulation of the bowel contents to access the spine, patients may suffer from ileus or actual injury to the abdominal contents themselves. Vascular complications can occur, more often during the annulotomy, discectomy, and placement of the cage than during the exposure itself. The range of potential vascular injuries is from minor to life threatening given the involvement of the great vessels. Retrograde ejaculation was discussed above. In addition, as with any fusion procedure, the risks of subsidence of the graft, pseudoarthrosis, graft extrusion, and implant failure do exist. Subsidence can be reduced with appropriate sizing of the graft to the body, maximum contact surface area between graft and vertebral body, and complete preparation of endplate surfaces. Over time, ALIF cages have also evolved to include supplemental screw fixation into the adjacent vertebral bodies such as Synfix (DePuy Synthes: West Chester, PA). Other options for improved stabilization, reduction of subsidence, and prevention of graft extrusion, include anterior plating and the standalone interbody cages.³⁴⁻³⁶ Tzermiadianos et al. have shown in a biomechanical model that the use of a ATB plate (DePuy Synthes) in addition to a cage can significantly decrease the range of motion in flexion and extension comparable to the use of posterior pedicle screw augmentation.³⁷ Nichols et al. also confirmed the equivalent stability of an anterior plate to posterior instrumentation.³⁸ Gerber et al. have demonstrated an increase in axial stiffness equivalent to that of posterior supplementation.³⁴

Circumferential Fusion

Another means to treat lumbar degenerative disc disease is to perform a circumferential fusion. By utilizing both the anterior vertebral body surfaces and the posterior fusion bed, the rate of fusion is higher. This is at the cost of a larger procedure with the associated morbidities. A circumferential fusion can be obtained in multiple ways: ALIF plus posterolateral fusion, ALIF plus open posterior



Figs. 78.2A and B: Anteroposterior and lateral X-ray of circumferential fusion: Anterior lumbar interbody fusion with posterior instrumentation.

instrumented fusion, ALIF plus percutaneous pedicle screws, posterior-based instrumented fusion and lumbar interbody fusion (PLIF or TLIF)—the entire procedure can be performed through the posterior approach, or lateral interbody fusion with percutaneous pedicle screws (Figs. 78.2A and B). Given the potential increased operating time, hospital stay, transfusion need, and overall complication rate compared with a stand-alone fusion, patients who undergo a circumferential fusion must be carefully selected. This approach to fusion is advantageous in the setting of revision surgery, those at high risk for subsidence, and in diabetics and smokers.

There is ample literature to support a higher fusion rate in those patients receiving circumferential fusion. The improvement in clinical outcome, however, has been questioned. Kozak et al. gave validity to the technique of a circumferential fusion by demonstrating a >90% fusion rate in single- and double-level fusions performed for discogram-positive patients with low back pain.³⁹ In multilevel patients, the fusion rate fell to 78% but overall they still found acceptable clinical results in 80% of those with primary low back pain. Gertzbein et al. performed circumferential fusions with semirigid instrumentation on patients who had failed prior surgery, including those with pseudoarthrosis, as well as patients who were heavy smokers.⁴⁰ They showed a 97% fusion rate, significant reduction in pain scores, and that 77% of patients returned to a satisfactory level of activity. Hinkley and Jaremko studied the effects of circumferential fusion in a workers compensation population and found that 91% of the 81 patients treated had reduced pain and disability, thus

demonstrating a positive response to treatment.⁴¹ Moore et al. performed combined anterior and posterior fusions in those with chronic back pain and degenerative disc disease using two tricortical iliac crest allografts anteriorly and a posterolateral fusion with Cotrel-Dubousset instrumentation.⁴² They documented a 95% solid arthrodesis rate, with 86% clinical improvement as patients showed a decrease in pain on the visual analog scale (VAS) and improvement in functional questionnaires.

Randomized controlled trials (RCTs) have also been performed to compare the fusion rates and outcomes of posterolateral fusion with circumferential fusion. Fritzell et al. performed a prospective multicenter RCT comparing patients with chronic low back pain treated by three different modalities: (1) posterolateral fusion, (2) posterolateral fusion with VSP, and (3) posterolateral fusion with VSP and an interbody fusion (either an ALIF or PLIF).⁴³ At 2-year follow-up, they were able to again confirm the higher rate of fusion with circumferential procedures, as the respective rates of fusion were 72%, 87%, and 91%. Interestingly, they were not able to show a significant difference in clinical outcomes between groups. On the other hand, Videbaek et al.⁴⁴ documented long-term 5- to 9-year follow-up on a RCT by Christensen et al.⁴⁵ between posterolateral fusion with Cotrel-Dubousset instrumentation versus circumferential fusion with ALIF and posterolateral instrumented fusion. The initial tendency toward better functional outcome shown by Christensen at 2-year follow-up was significantly better at long-term follow-up. This was the case in terms of general health, daily activity, and Oswestry Disability Index. More recently, Høy et al. compared

circumferential fusion with a TLIF and posterolateral fusion with Texas Scottish Rite Hospital instrumentation and did not find a significant difference in clinical outcome.²⁰ Thus, with major RCTs in the literature providing conflicting evidence, clinical outcome of circumferential fusion is debatable. However, it can be asserted that circumferential fusion does have an increased fusion rate and a decreased reoperation rate despite the potential associated morbidities of a more extensive surgical procedure.

As mentioned above, there are methods by which to obtain a circumferential fusion without performing an ALIF. These are all posterior-based procedures and include either the PLIF or TLIF. Though the ability to perform these procedures is sometimes limited by patient anatomy (i.e. narrow pelvis), excessive adherence in the setting of a revision, or difficulty of exposure in the setting of a muscular or coagulopathic patient can be performed through a single posterior incision—thereby avoiding the additional morbidity of an anterior approach.

Posterior Lumbar Interbody Fusion

The PLIF is performed through a midline lumbar incision. A laminectomy is performed at the desired level of interbody fusion. A bilateral partial facetectomy is also performed allowing for retraction of the dura to access the intervertebral disc space and perform annulotomy. Two cages are placed within the interbody space following annulotomy, disc removal, and endplate preparation; one cage from either side. In the case of TLIF, the same incision is used, but the laminectomy is not necessary. In an open bilateral exposure, pedicle screws and rod construct may be placed on either side, preferably on the side into which the cage will be inserted. Distraction is then applied across the screws to allow access to the disc space. Headless screws can be temporarily used to limit interference with cage insertion. The inferior facet is completely removed, thereby necessitating less retraction of the dura than is present in the case of a PLIF to access the disc space. Again the same steps are taken including annulotomy, discectomy, and endplate preparation followed by placement of a single cage in the intervertebral space. One technique involves aiming the cage to the diagonal anterolateral corner of the disc space and then using a specialized inserter to flatten the cage out. The PLIF technique has fallen out of favor given the increased potential for dural tears, conus injury through excessive retraction, and enhanced epidural scarring from dural manipulation. The TLIF helps

avoid some of these risks, but, like the PLIF, still places the nerve root at risk for injury, and requires instrumentation given the complete takedown of the facet. In addition, if it is necessary, the TLIF procedure allows for thorough decompression of the nerve root. The fusion rate for TLIF and ALIF are similar, however, Hsieh et al. found that ALIF is superior to TLIF in its ability to restore foraminal height, local disc angle, and lumbar lordosis which may have implications in terms of overall sagittal balance.⁴⁶

Minimally Invasive Surgery

While the traditional means of obtaining a fusion, whether anterior, posterior, or circumferentially, has been in an open fashion, there are also several minimally invasive options. Those who favor minimally invasive approaches cite limited muscle dissection and crush injury (especially posteriorly), minimal blood loss, projected shorter operating times (once past the learning curve), and reduced length of inpatient stay as advantages. In particular, when decompression is not needed, the following techniques can be viable alternatives.

The first type of minimally invasive spine surgery performed was in the form of percutaneous pedicle screws. These were described by Magerl in 1982,⁴⁷ as a component of an external fixator used in traumatic situations. Magerl also documented the use of a translaminar facet screw in an open fashion, which has since been rivaled by a minimally invasive counterpart. In the 1990s, the advent of several endoscopic procedures in both general and urologic surgery spurred the generation of minimally invasive anterior and retroperitoneal approaches to the lumbar spine in the setting of fusion for low back pain.

Minimally Invasive Surgery (MIS) ALIF

There are three common minimally invasive approaches to the anterior lumbar spine including the mini-open retroperitoneal, laparoscopic transperitoneal, and endoscopic retroperitoneal. To perform a mini-open retroperitoneal approach, a 3–4 cm transverse incision is made in line with the trajectory needed to get to the disc level marked by fluoroscopy. This incision is made slightly to the left of the midline allowing for dissection to the anterior rectus sheath and then lateral to the rectus abdominis. This plane is then followed to the peritoneum, which is then separated from the lateral wall to access the retroperitoneum. Self-retaining retractors are then used to hold the

peritoneal contents out of the way, and vessels are then carefully dissected free from the anterior spine. The endoscopic retroperitoneal approach is performed in the lateral decubitus position via a 2–3 cm transverse incision centered over a line drawn from the eleventh rib to the anterior superior iliac spine. Blunt dissection is used to the retroperitoneal fat layer, and a dissection balloon is then inserted and inflated to create a retroperitoneal space. The balloon is then removed and self-retaining retractors or carbon dioxide insufflation is used to maintain this space. Ports can be made to insert working instruments, endoscope, and retractor blades. The psoas is elevated, and the anterior spine is exposed. Finally, in the case of a laparoscopic transperitoneal approach, multiple 1–2 cm incisions are made through which a scope, dissecting instruments, and retractors (as needed) are inserted. These instruments are used to dissect through the posterior peritoneum over the desired intervertebral space, with blunt dissection used for the retroperitoneal fat to limit parasympathetic plexus injury. This approach is limited at L4–L5 given the bifurcation of the great vessels.

The major disadvantage cited for laparoscopic transperitoneal approaches in comparison to retroperitoneal approaches is the risk of RE secondary to injury to the parasympathetic plexus (superior hypogastric plexus). This was mentioned above in the section on anterior approaches. In an initial series of patients who received laparoscopic ALIF, Zdeblick noted a 6% incidence of RE.⁴⁸ In a separate prospective study comparing laparoscopic and mini-open ALIF, Zdeblick and David found no differences in operating time blood loss, or length of stay for a single level, as well as higher complications at L4–L5.⁴⁹ Escobar et al. in a review of various minimally invasive techniques including those undergoing endoscopic retroperitoneal and laparoscopic transperitoneal approaches documented a greater need to convert to open intervention secondary to complications.⁵⁰ The limited exposure gained by laparoscopic techniques as well as the need to ligate the iliolumbar vein in the approach to L4–L5, in particular, can be problematic. There is a significant learning curve associated with laparoscopic transperitoneal approaches and even endoscopic retroperitoneal approaches, while the mini-open retroperitoneal approach is more easily developed for both access and spine surgeons alike.⁵¹

MIS PLIF/TLIF

With respect to posterior minimally invasive techniques, the risk profile of the PLIF versus the TLIF parallels the

open approach secondary to the need for medial retraction of nerve root, as well as takedown of midline structures. Both minimally invasive approaches involve the use of a paramedian incision that is centered over the disc space and the use of METrx (Medtronic: Minneapolis, MN) tubular dilators to reach the target point. In an MIS PLIF, bilateral incisions are made 2.5 cm lateral to the midline, while the MIS TLIF uses a unilateral 4.5–5 cm lateral to the midline incision. The MIS PLIF requires a hemilaminectomy and medical facetectomy with resection of the ligamentum flavum to be able to retract the nerve root medially. Once the disc space is accessed and interbody device is placed, tubular retractors are removed for placement of percutaneous pedicle screws to stabilize the disc segment. In the unilateral MIS TLIF, a total facetectomy is performed using a bayoneted osteotome, and the lateral most aspect of the ligamentum flavum can be taken down to visualize the exiting nerve root if desired. Distraction across the disc space can be performed by larger tubular dilator insertion. A smaller contralateral incision can be used in the case of an MIS TLIF to create distraction between the spinous processes with a laminar spreader or to place a contralateral percutaneous screw and rod construct through which distraction can be applied. An additional modification to the unilateral MIS TLIF technique has been to place a contralateral facet screw as a supplement to the unilateral pedicle screws, thereby avoiding further dissection, potential muscle injury, increased operating time, and abutment of a pedicle screw against the intact facet above (thought to play a role in the creation of adjacent segment disease).⁵² This can be done through a standard incision or in a percutaneous fashion as well. Both Slucky et al. and Schleicher et al. showed that a unilateral TLIF with pedicle instrumentation supplemented with contralateral facet screws had no significant difference in range of motion biomechanically when compared with a TLIF with bilateral pedicle screws.^{53,54} On the other hand, a unilateral TLIF without contralateral supplementation did have significantly less stiffness. Sethi et al. have documented the cost-effectiveness of such a construct involving facet screws.⁵⁵

Multiple studies have confirmed that the minimally invasive TLIF technique, when compared with the traditional open TLIF has resulted in less initial postoperative back pain, reduced intraoperative blood loss and need for transfusion, quicker time to ambulation, reduced hospital length of stay, reduced soft tissue injury (as measured by creatine kinase levels), and quicker functional

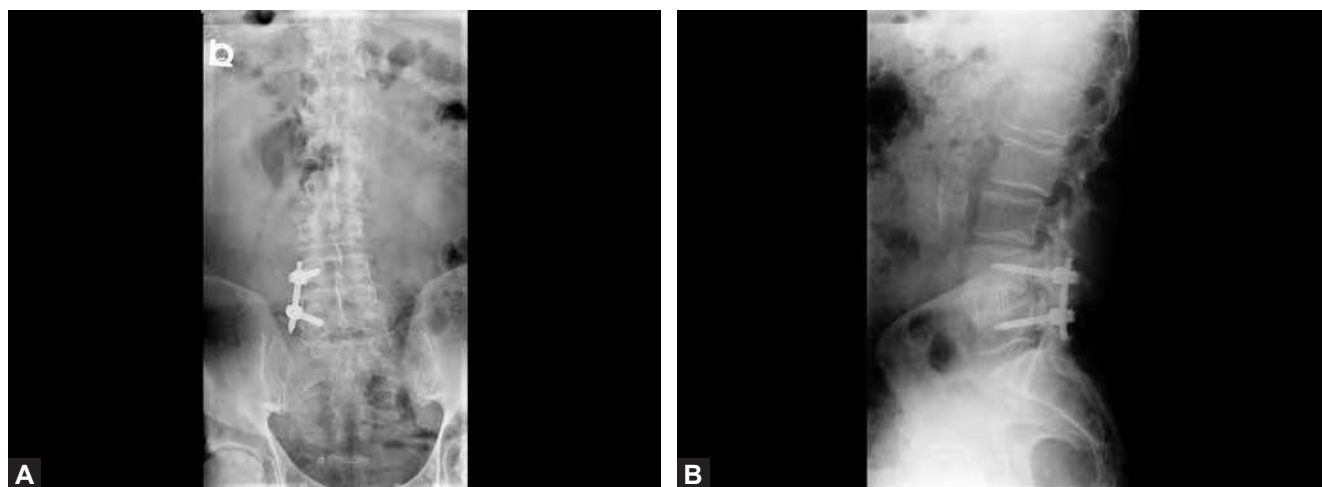
recovery.⁵⁶⁻⁵⁹ Seng et al. recently published a retrospective analysis of prospectively conducted study with mid-term follow-up of 40 matched cases of open TLIF versus MIS TLIF.⁵⁹ At 5 years, they found no significant difference in several validated outcome scores between the two groups and both groups had a fusion rate of 97%. With the additional benefits listed above, the MIS TLIF is a safe and effective option to consider.

XLIF/DLIF

An additional minimally invasive alternative to an open ALIF for an interbody fusion is an extreme lateral interbody fusion (XLIF), also known as a direct lateral interbody fusion (DLIF). This is an attractive option for interbody fusion with minimal takedown of native spine anatomy with the exception of the intervertebral disc. The patient is usually approached from the left side and therefore placed in the right lateral decubitus position. The operating table used allows for bending in the coronal plane, thus jacking open the left lateral aspect of the intervertebral space. Using AP fluoroscopy to identify the level and ensuring that the superior aspect of the iliac crest is not in the way (usually the case at L4-5), blunt dissection is carried down to the retroperitoneum to find the psoas muscle. The combination of dilators and electromyographic (EMG) monitoring is then used to dissect through the psoas while avoiding the lumbar nerve root plexus within the muscle itself to the lateral aspect of the intervertebral disc. The purported advantages of this minimally disruptive

approach are the ability to remove a large amount of disc material, placement of a large stable interbody implant, and retention of the anterior longitudinal ligament which is sacrificed in an ALIF (Figs. 78.3A and B). Biomechanical studies have been conducted to compare stand-alone lateral interbody fusions with or without instrumentation with ALIF constructs. Cappuccino et al. found that the lateral interbody cage had the largest stand-alone device reduction in range of motion compared with an ALIF and TLIF.⁶⁰ The addition of bilateral pedicle screws to create a circumferential fusion had the greatest stability. Others have recommended a lateral interbody fusion with unilateral pedicle instrumentation; however, this has an intermediate reduction in range of motion.

The most common concern expressed by spine surgeons with respect to the XLIF procedure is either vascular or neurologic complications, with specific focus on the lumbar plexus. Benglis et al. reported on the anatomy of the lumbar plexus after performing dissections on three cadavers.⁶¹ They found that the lumbosacral plexus was lying within the substance of the psoas muscle between the junction of the transverse process and the body and exited along the medial edge of the psoas distally. It migrated from dorsal at L1-L2 posterior endplate to ventral as it traverses down to L4-L5. It appeared, on an average of the dissections, to remain within the posterior one third of the disc space, and therefore dilators used during the approach should be “wanded” anteriorly. This should be corroborated by EMG monitoring as well as fluoroscopy. The genitofemoral nerve was found to be most at risk.



Figs. 78.3A and B: Extreme lateral interbody fusion: Performed via a minimally invasive approach, this extreme lateral interbody fusion was supplemented with unilateral pedicle screws.

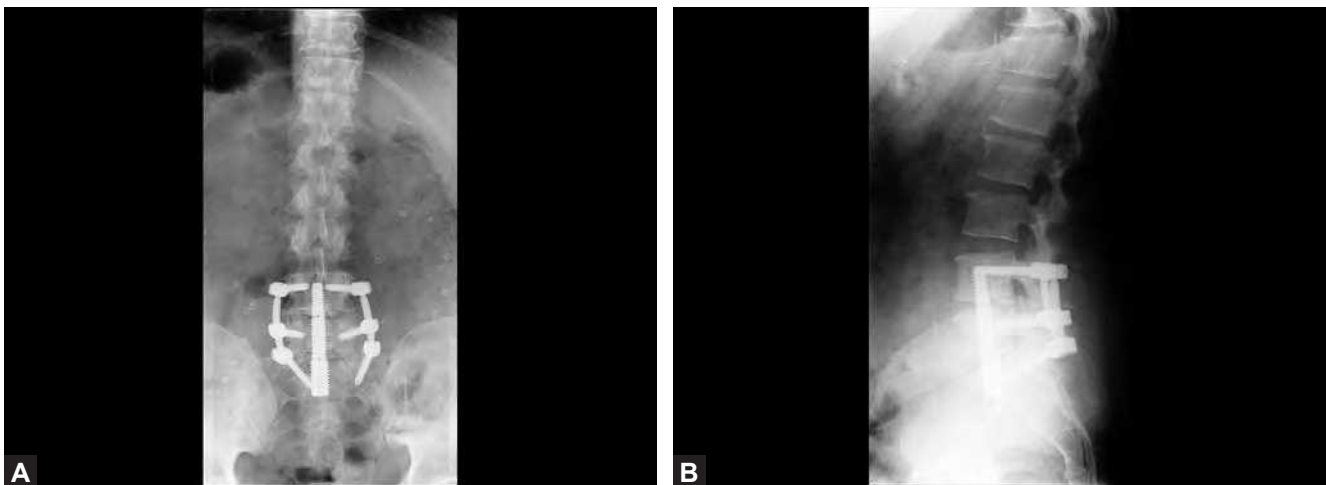
While this study gave comfort to the idea of staying within the anterior two thirds, a more recent anatomic mapping study by Banagan states that there is no absolute zone of safety in this approach.⁶² With 16 cadaveric dissections, perforating branches of lumbar nerve roots were identified in anterior, middle, and posterior third of the psoas muscle placing both the roots and the genitofemoral nerve at risk. The lumbar plexus was also found to be placed under tension with sequential dilator placement. Again this highlights the necessity of supplemental EMG monitoring if this approach is to be taken. Regev et al. also examined the safe corridor within which discectomy and insertion of a cage can be performed from the lateral approach.⁶³ They again confirmed the narrowing of this safe corridor as one proceeds from L1-L2 down to L4-L5 and highlighted that preoperative MRI should be scrutinized for the location of important neurovascular structures.

Clinically, there is a limited amount of data in terms of outcome studies on XLIFs with respect to complications as the technique is relatively new. Knight et al. reported no vascular complications from the approach, and 2 out of 58 patients (3.4%) developed permanent motor deficits due to L4 nerve root injury.⁶⁴ In a more recent larger prospective analysis of 600 cases, Rodgers reported no vascular complications and 4 out of 600 patients developed a transient motor weakness which resolved within 3 months.⁶⁵ Postoperatively the L4 nerve root injury is most often manifested as quadriceps weakness and/or thigh or hip pain. Rodgers suggested premedicating with 10 mg of

dexamethasone IV preoperatively significantly reduced the transient motor deficit finding.⁶⁵ The incidence of complications with lateral interbody approaches compared with those reported for ALIF and TLIF are similar, and in some instances such as reported by Ozgur, they are close to nonexistent.⁶⁶

AxialLIF

A final minimally invasive means to obtain a lumbar fusion, in particular for L5-S1, is the percutaneous axial lumbar interbody fusion, also called AxialLIF. As initially described, a small incision is made above the coccyx, and a guide is maneuvered through the presacral or paracoccygeal space to the inferior aspect of the S1 body. This then allows for eventual removal of the central aspect of the disc and placement of a variable pitch axial screw through the vertebral body of S1 into L5 (Figs. 78.4A and B). The variable pitch is designed to create distraction as it is inserted. The cited advantages include the retention of the ALL, PLL, and annulus fibrosus while restoring disc height/lordosis through the distraction. Its usage has been expanded to attempts at two-level fusions, from L4-S1. Tobler et al. performed a retrospective case series review of 164 patients treated with AxialLIF for back pain thought to be secondary to degenerative disc disease, and at 2 years follow-up, 63% had an improvement in overall pain score, while 54% had an improvement in their ODI.⁶⁷ Radiographic fusion rate was 94%. A more recent study by Hofstetter et al. performed a retrospective analysis



Figs. 78.4A and B: AxialLIF: A large specialized screw with variable pitch was inserted through the presacral space to serve as the interbody fusion for two levels: L4-L5, and L5-S1. Supplemented with posterior instrumentation.

of 38 patients who underwent either single or two-level AxiaLIFs.⁶⁸ Overall, surgical outcomes demonstrated only modest symptomatic improvement, and fusion rates were 81% for single level, 33% for L5-S1 in a two level and 0% for L4-L5 in a two level. They asserted that the AxiaLIF provides inadequate long-term anterior column support, and there is thus significant risk for subsidence and loss of segmental lordosis. Other serious complications have been reported in the literature including rectal perforation requiring long-term intravenous antibiotic treatment with the creation of diverting colostomy as well as occasional retrieval of the device by sigmoidoscopy.⁶⁹ Further study of this technique and device is needed to deem it safe and effective for both one- and two-level interbody fusion.

Osteobiologics

Regardless of the type of fusion targeted, osteobiologics are a necessary component in obtaining a solid arthrodesis. Historically, fusion beds were filled with autograft, allograft, or a combination of the two. However, the morbidity associated with iliac crest bone harvest and the goal of improving fusion rates have spurred the advancement of osteobiologics used in spine surgery.

Osteobiologics contain one or more of the following properties: osteogenic, osteoconductive, or osteoinductive. That is, they either contain osteoprogenitor cells, serve as a scaffold on which bone cell reproduction can occur, or chemically signal surrounding cells to begin production of local bone and bone remodeling. In addition to the use of local autograft (morselized laminectomy bone) and allograft, several graft extenders with these properties are now available. They fall into the classes of bone morphogenetic proteins (BMPs), mesenchymal cells, and demineralized bone matrix.

In 1965, Marshall Urist documented the biological basis of bone morphogenesis by implanting dead bone matrix (decalcified) in the muscle pouches of rabbits.⁷⁰ He noted the presence of inductor cells and induced cells of the host bed, in which both cell lines were of the histiocyte lineage. In his later work, he used the term “bone morphogenetic proteins” to describe those molecules that were responsible for altering cell metabolic cycles in the induced cells to produce bone.⁷¹ Originally, seven BMPs were discovered, six of which belonged to the transforming growth factor superfamily. Today, there are approximately 20 BMPs known to exist. Bone morphogenetic protein-2 and BMP-7 have been manufactured in recombinant

formats and are FDA approved for clinical application. Bone morphogenetic protein-2 has most commonly been used in spinal surgery.

Initial studies on rhBMP2 indicated improved fusion rates with the reduction in donor site morbidity associated with iliac crest bone harvest. Boden et al. performed a human clinical pilot trial with 14 patients who received lumbar interbody fusion with threaded tapered cylindrical cages and rhBMP-2 or iliac crest autograft.⁷² They found that fusion was more reliably occurring in those treated with rhBMP-2 within the cage and reported no adverse events. Shortly after, Burkus et al. performed a multicenter, prospective, randomized, nonblinded study of 279 patients with degenerative disc disease between two groups that underwent anterior interbody fusion with two tapered threaded fusion cages using either rhBMP-2 applied to an absorbable collagen sponge or autogenous iliac crest bone graft, and found a fusion rate of 94.5% in the investigational group compared with the 88.7% in the control group.⁷³ Both groups had similar outcomes, while at 2 years, 32% in the control group reported donor site discomfort. Labeled on the market as Infuse (Medtronic), rhBMP-2 is applied to a bovine absorbable collagen scaffold. Multiple studies followed documenting the benefits of use of rhBMP-2 on cost-effectiveness, operating room time, blood loss, donor site morbidity, equivalence or superiority to fusion rates with iliac crest autograft, and equivalent validated outcome scores.⁷⁴⁻⁷⁶ Additional purported benefits also existed in challenging situations, such as retained fusion rates in smokers or patients aged >60 years. Glassman and colleagues demonstrated fusion rates for smokers receiving rhBMP-2 at 95% compared with smokers receiving iliac crest bone graft at 76%.⁷⁷ Carreon et al. also showed a reduction in complication rate and revision rate with patients over 60 years of age in a cost-utility analysis.⁷⁸

With increased use of rhBMP-2 in spinal fusion techniques, multiple studies have also documented the various complications that can be encountered.⁷⁹ They span a range including postoperative radiculitis⁸⁰ in both single-level open and minimally invasive TLIFs, postoperative seroma formation requiring evacuation both in cervical and lumbar applications,^{81,82} heterotopic bone formation in the paraspinal musculature⁸³ as well as within the neural foramen resulting in recurrent nerve root symptoms,⁸⁴ and vertebral osteolysis up to a rate of 5.8%.⁸⁵ Others have documented subsidence, resorption of bone, and interbody cage migration associated with its use.⁸⁶ In 2011, the use of rhBMP-2 in spine surgery received significant attention,

as Carragee et al. performed a systematic review to compare conclusions regarding the safety and related efficacy published in the original rhBMP-2 industry-sponsored trials and subsequently available FDA publications and databases.⁸⁷ They found an estimated adverse rate associated with the use of rhBMP-2 in spine surgery of 10–50% depending on the approach. Anterior cervical fusion has a 40% greater risk in the early postoperative period while anterior lumbar interbody lumbar fusion rates of implant displacement, subsidence, infection, urogenital events, and RE were listed to be higher than controls. They mentioned all of the complications discussed in the first portion of this paragraph associated with posterior lumbar interbody fusion and found the risk of adverse effects associated with the use of rhBMP-2 in posterolateral fusions to be equivalent to or greater than iliac crest bone graft harvesting. In addition, the most alarming documentation was that higher doses of rhBMP-2 were associated with a greater apparent risk of new malignancy in a location other than the spine itself where the rhBMP-2 was implanted. The group's review of data suggested possible study design bias in original trials, and the risk of adverse events associated with rhBMP-2 being 10–50 times the original estimates reported. Since this study publication, several others have examined the risk of malignancy with the use of rhBMP-2. Devine et al. performed another systematic review of five published peer-reviewed studies and two FDA safety summaries that reported the occurrence of cancer in patients treated with spinal fusion using either rhBMP-2 or rhBMP-7.⁸⁸ This risk of cancer was the same in both rhBMP-2 and control groups of 0.7%. Off label use of rhBMP-2 for posterolateral fusion was associated with a slightly higher risk of cancer compared with controls in three RCTs at 5% using 40 mg of BMP-2 compared with 1% in the control group. The two RCTs that evaluated rhBMP-7 reported cancer risk of 13% and 6% in those who received the product versus 8% and 0% in the control groups; however, these differences were not statistically significant. Thus, the conclusion was that risk of malignancy may be dose dependent and further evaluation was needed. In a study of the use of high dose BMP (greater or equal to 40 mg) of 502 spine cases, Mesfin et al. found a cancer prevalence of 3.4% but did not find a correlation between dosage and cancer and in fact found a negative correlation coefficient of -0.05 , which would incorrectly indicate a protective effect against cancer.⁸⁹

Following the rising concern about the safety and effectiveness of the use of rhBMP-2 in spine surgery, the manufacturer of the product Infuse containing rhBMP-2

provided Yale University a grant to conduct two fully independent third-party systematic reviews of rhBMP-2. This project was termed YODA, or Yale University Open Data Access. These results were published in June 2013. The first site, Oregon Health and Science University, found that rhBMP-2 and iliac crest bone graft were similar in overall success, fusion, and other effectiveness measures and in risk for any adverse event for lumbar spine fusion.⁹⁰ With respect to ALIF, rhBMP-2 was associated with nonsignificantly increased risk for RE and urogenital problems, while for anterior cervical spine fusion, there was an increased risk of wound complications and dysphagia. At 24 months, cancer risk was increased with rhBMP-2, with a risk ratio of 3.45, but event rates were low and the type of cancer was heterogeneous. Importantly, they concluded rhBMP-2 has no proven clinical advantage over bone graft and may be associated with important harmful effects, making it difficult to identify clear indications for its use. The second site, University of York, in the United Kingdom, found that at 24 months, ODI scores were 3.5% better with rhBMP-2 than with ICBG, and radiographic fusion was 12% higher.⁹¹ Pain and cancer incidence were more common than with rhBMP2 use, with a relative risk of 1.98, but there was overall a small number of these events. Thus, evidence of increased cancer incidence is inconclusive.

Today, the use of rhBMP-2 is severely limited compared with its use in the past. The FDA approval remains for ALIF with BAK cages. It remains critical for spine surgeons to deliver clear information regarding safety and effectiveness of rhBMP-2 prior to its clinical use in patients.

Alternative osteobiologics to BMPs include mesenchymal cells and demineralized bone matrix. Early studies indicate that products such as OsteoCel Plus (Nuvasive: San Diego, CA), an allograft bone matrix containing mesenchymal stem cells and osteoprogenitor cells combined with demineralized bone matrix and cancellous bone, may be appropriate substitutes for iliac crest autograft.⁹² Randomized controlled trials need to be conducted with a focus on both fusion rate and safety profiles prior to widespread use.

Adjacent Segment Degeneration

Lumbar fusion has long been the standard for the treatment of chronic low back pain thought to be secondary to lumbar degenerative disc disease. However, a major concern that has developed regardless of technique or method chosen to establish the fusion is adjacent segment degeneration or disease (ASD). This was pointed out as early as 1963, by Harris, in which he noted acquired spondylosis as

a sequel to spinal fusion.⁹³ Adjacent segment disease refers to degenerative processes such as disc herniation, disc degeneration, instability, spinal stenosis, facet degeneration, and deformity that are known to occur after fusion, most commonly at the immediately adjacent functional spinal unit; however, these can also occur at levels not immediately adjacent.⁹⁴ There are various theories as to how this process occurs. Some advocate that it is the natural history of the lumbar spine as it ages that is primarily responsible for this phenomenon. Others, such as Cunningham et al., have shown in biomechanical cadaveric models that instrumented fusions can change the intradiscal pressure present in adjacent levels, which in turn is hypothesized to serve as the impetus for altered metabolic change and thus predisposition to degeneration.⁹⁵ The third proposed mechanism is that the disruption of anatomy of the adjacent level occurs during the initial surgery itself, thus altering the rate at which adjacent levels degenerate.

Both Penta et al. and Wai et al. have used MRI to study disc degeneration 10 and 20 years, respectively, after ALIF, and concluded that individual characteristics of patients or constitutional factors may be more so responsible for the presence of degeneration than increased biomechanical stress above the fusion.^{96,97} Wai documented 74% degeneration in adjacent levels and advanced degeneration in 31%, but found no association between function and the level of degeneration.⁹⁷ Interestingly, 18% of advanced degeneration cases were located at level not immediately adjacent, highlighting the roles of aging or preexisting degeneration.

Wang and Ghiselli studied ASD both cephalad and caudad to the fusion segment and established a predictive rate of 16.5% at 5 years and 36% at 10 years of symptomatic adjacent level disease.⁹⁸ More recently, Lawrence et al. performed a systematic review in which they documented a mean annual incidence of clinical adjacent segment pathology of 0.6–3.9%.⁹⁹ Through their review they identified strong levels of evidence that age >60 years is a significant risk for the development of adjacent segment pathology. Other potential factors that were supported by statistical analysis of combined data that may lead to ASD are preexisting facet degeneration at the time of surgery, degenerative disc disease within the lumbar spine, multi-level fusions, ending a fusion construct at L5, a laminectomy adjacent to a fusion, and excessive distraction across the disc space during a posterior interbody fusion.^{99,100} The integrity of the posterior ligamentous complex has been

postulated to be responsible for lower incidence of ASD in those who undergo ALIF versus those who receive a complete laminectomy during a posterior fusion.^{101,102}

Motion preserving technologies have since been developed with the goal of lowering the incidence of ASD after surgical intervention. These designs hinge on the idea that retaining motion at the indicated segment would less so alter the mechanical environment of adjacent levels. For the purpose of treating degenerative disc disease, motion sparing devices include pedicle-based dynamic stabilization systems, total disc arthroplasty (TDA), and nucleus replacement.

Pedicle-based Dynamic Stabilization (PBDS) Systems

In keeping with preservation of motion within the lumbar functional unit, pedicle-based dynamic stabilization systems were developed to provide soft tissue stabilization while in the long term allowing retention of mobility. They are thought to reduce pain in the setting of degenerative disc disease by unloading the facet joints and the disc. The first PBDS design was developed in Europe and was called the Graf system.¹⁰³ This device utilizes looped 8 mm braided polyester bands instead of rods. Once the pedicle screws are in place, the bands are connected under an applied compressive force similar to the process in ligamentoplasty. The goal was to immobilize the spine in lordosis, compress the posterior annulus, and temporarily stabilize the spine while allowing return of motion or relaxation over time. Hashimoto conducted a 3.5-year follow-up on Graf ligamentoplasty performed for degenerative conditions with minimal instability and also noted preservation of lordosis, significant improvement in VAS scores, but significant loss of preoperative range of motion.¹⁰⁴ Kanayama reported a 10-year follow-up for 43 patients who had Graf ligamentoplasty for various degenerative pathologies.¹⁰⁵ They found a maintenance of lumbar lordosis, flexion–extension motion of approximately 4°, and a 7% ASD incidence.

The Dynesys system was the next to follow and consists of stabilization of pedicle screws by polyester cords that connect the screw heads through a hollow spacer. While the Graf system significantly limited flexion and created excessive posterior annulus compression, the Dynesys system has a push–pull relationship between the spacer and the polyester cord that, respectively, resist



Fig. 78.5: NFlex: A 53-year-old patient with degenerative disc disease at L3-L4 treated with a pedicle-based dynamic stabilization system at 2 years postoperative demonstrating retained motion on flexion–extension lumbar radiographs.

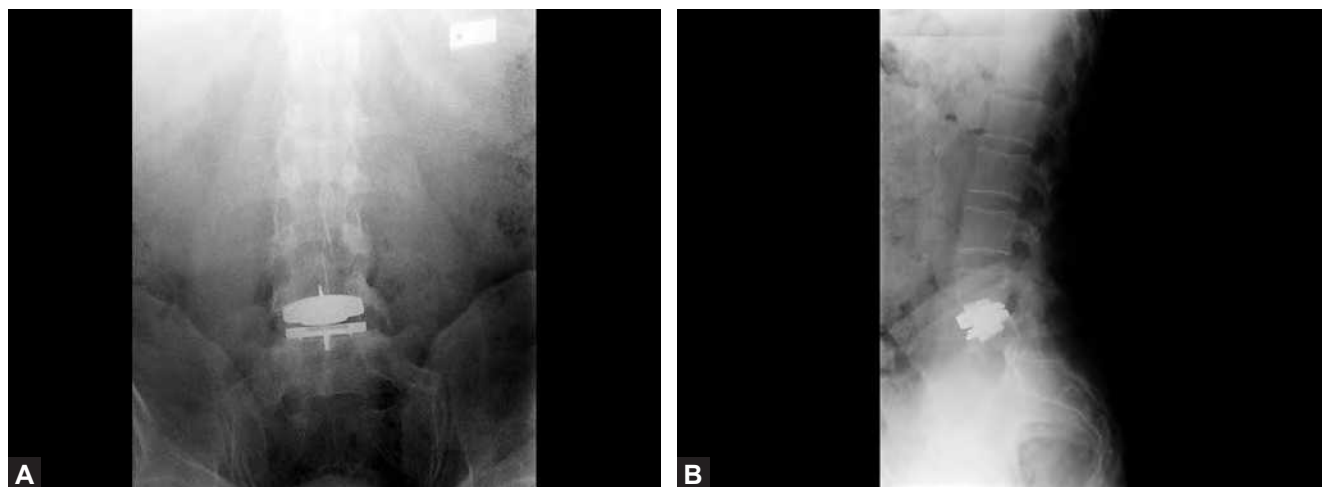
compressive and flexion movements. Again, the goal is to reduce loading of the disc and preserve long-term motion. Studies that have compared segmental fusion to nonfusion techniques with Dynesys such as that by Cakir et al. have found limited preservation of motion and, therefore, recommend against Dynesys implementation.¹⁰⁶ Grob et al. found a 19% revision rate at 2 years,¹⁰⁷ while Bothmann et al. found significant complications after use of this system with a revision rate as high as 28%.¹⁰⁸ Gédet et al. argue that the assumption that a device such as Dynesys that is compliant in bending and allows substantial intersegmental motion is not well supported because the device is not operating near the natural center of rotation of the intervertebral disc.¹⁰⁹ Jahng et al. conducted a comparison study between various PBDs systems including Dynesys, NFlex, PEEK, and the conventional titanium rod, using a validated finite element analysis model.¹¹⁰ They determined that all of the systems have a limited range of motion compared with the intact spine; however, NFlex had a center of rotation closest to the intact and had the highest range of motion preserved (Fig. 78.5). With the lack of RCTs showing favorable superiority with the usage of the dynamic systems, there is a void of high level data to support their routine usage.

Total Disc Arthroplasty

Total disc arthroplasty aims to replace the disc with a mechanical device that closely replicates the range of

motion of the native state of a functional spinal unit. In the setting of discogenic back pain, the offending disc material is removed, thereby alleviating pain, and the implanted device maintains disc height and lordosis thus affording stability of the spine segment. No additional bony healing is necessary as is the case in a fusion. The total disc replacement (TDR) is patterned after total hip and knee arthroplasty with the use of metal and polyethylene components to establish bearing surfaces. In the United States, two devices are currently approved for implantation including the SB Charite III (DePuy) and the Prodisc-L (Synthes: West Chester, PA). Several IDE trials are ongoing with other TDA devices (Figs. 78.6A and B).

As is the case with performing a fusion in the lumbar spine, patients must be carefully selected to undergo lumbar disc arthroplasty. In fact, the criteria are more stringent than a fusion, as the patient must have isolated discogenic pain in the absence of any level of instability, radiculopathy, stenosis, osteoporosis, scoliosis, and, in particular, facet arthropathy. The technique for disc arthroplasty is similar to that of an ALIF as an anterior approach is utilized. Once the disc is removed and endplates are prepared, the surgeon must ensure the posterior annulus fibrosus is released for correct positioning of the device. Depending on the exact design of the prosthesis, it may be necessary to create a keel in the endplates.



Figs. 78.6A and B: Total disc arthroplasty: These images demonstrate a total disc replacement with a Prodisc-L (Synthes).

Initial studies with TDA sought to prove at a minimum, noninferiority to outcomes obtained by lumbar interbody fusion. Guyer et al. reported on a 5-year follow-up study to the initial 2-year follow-up on the safety and effectiveness of the Charite artificial disc with comparison to ALIF with BAK cages and iliac crest autograft.¹¹¹ They demonstrated noninferiority of the Charite in a prospective randomized multicenter fashion, with no statistical differences in clinical outcomes in the two groups, and the Charite retaining 6° on average for range of motion versus 1° for the ALIF group. In addition, Guyer et al. reported a greater rate of employment and lower rate of disability in comparison with the fusion group. Similarly, Zigler et al. performed a prospective randomized multicenter FDA IDE trial on Prodisc versus circumferential arthrodesis for a single level.¹¹² His group also demonstrated noninferiority with this device as there was no statistically significant difference in outcomes at 5-year follow-up and range of motion was retained within normal range. Zigler et al. noted that reoperations were lower in the disc replacement group (8% versus 12% among fusions). Thus, in comparing both the Charite and the Prodisc to fusion, these TDRs have been deemed as reasonable and safe alternatives.

Adjacent segment disease has been studied after TDR. In the same FDA IDE cohort cited in the Zigler study above, it was found that 9% of the TDR patients developed ASD, whereas 29% of the fusion patients did.¹¹³ Concordantly, 2% of the TDR patients underwent revision or additional surgery, while 4% of the fusion patients did. This difference was not found to be statistically significant; however, the

lower rate of ASD with TDRs can be advantageous in the setting where patients would otherwise require a multi-level fusion secondary to asymptomatic or subacute levels of degenerative changes in adjacent discs. Shorter term 2-year follow-up studies comparing ASD after TDR with control patients who received rehabilitation have not demonstrated a difference in incidence of ASD, indicating that perhaps at 2 years natural history has only played an effect, while with longer term follow-up the difference between fusion and TDR may become amplified with the interplay of natural history and biomechanical stressors.¹¹⁴ Interestingly, the TDR patients in Hellum's study did have a higher incidence of facet arthritis (34%) than controls who underwent rehabilitation (4%) at 2-year follow-up. Park et al. found a 29% incidence of facet arthritis at 26-month follow-up with Prodisc-L implants,¹¹⁵ while Shim et al. in a comparative study between Prodisc-L and Charite found an incidence between 32% and 36% at 3 years follow-up.¹¹⁶ Development of facet arthrosis could be one of the important variables that alters the stresses seen at adjacent levels.

Given that TDA may lead to a lower incidence of ASD despite similar functional outcomes in FDA trials at 5 years, longer term follow-up must be analyzed to ensure that there is no deviation in this performance down the line. Currently, most data is presented at a maximum of 5-year follow-up. Outside FDA trials, there is some indication that a difference may exist even at 5 years, favoring TDA. Sköld et al. conducted an RCT with data from the Swedish Spine registry of TDR versus posterior lumbar fusion.¹¹⁷ Back pain assessed with validated outcome scores including

VAS and ODI was significantly better after TDR at 1 year, no different at 2 years, and the statistically significant difference reappeared at 5 years. They also found no difference between complications and reoperations between the two groups.

To conclude that TDA outperforms fusion also requires demonstration that it is more cost-effective in the management of refractory discogenic pain. Levin et al. looked at raw implant cost with one- and two-level TDA with Prodisc-L versus circumferential fusion and found that the difference was minimal with a single level at \$13,800 for TDA and \$13,990 for fusion.¹¹⁸ However, total charge for TDA was \$35,592 versus \$46,280 for fusion as operating room costs differed at \$12,000 versus \$18,950, operating time was 185 versus 344 minutes, blood loss was 412 versus 794 mL, and mean length of stay was 4.32 versus 4.78 days, all in favor of TDA. When two-level procedures were analyzed, costs were similar. Fritzell et al. assessed the cost-effectiveness of TDR (Charite/Prodisc/Maverick) when compared with posterior lumbar interbody fusion with pedicle instrumentation at 2 years in an RCT.¹¹⁹ Their analysis included cost to society in which there was no difference, while the cost to health care was significantly less for TDR. However, when total gain in quality adjusted life years was considered, they were unable to determine which procedure was greater at 2 years and asserted that longer term follow-up is necessary to complete this analysis. Therefore, selection of TDA over fusion is still debatable.

Another important consideration in the adoption of TDA as a safe alternative to fusion is the complication profile. Though the goal of TDR is to retain motion of the lumbar segment there have been reports of heterotopic ossification (HO) occurring at the level of surgery and in some cases, this has even lead to spontaneous fusion. In 2003, McAfee et al. developed a five-grade classification system for HO formation around a disc prosthesis.¹²⁰ The important classes to distinguish between are class II and III, as in the latter, the range of motion of the vertebral endplates is blocked by the formation of HO, thus limiting flexion, extension, or lateral bending. Tortolani et al. performed a prospective, randomized study of 276 patients who underwent a CHARITE disc replacement and found a low incidence of HO of 4.3% at 2 years.¹²¹ None of these cases had a difference in range of motion or clinical outcome from those that did not have any evidence of HO. Park et al. evaluated 65 patients with 82 segments of TDA including mostly Prodisc and some Charite prostheses and reported an incidence of 30.5% at 17 months. Only

6% demonstrated class III HO. Despite their significantly decreased motion, the outcome scores for these patients were not significantly different from those who did not have any HO. Most of the HO was present in the anterior and posterior aspects of the prosthesis. Huang et al. looked at the risk factors for HO so as to develop preventive strategies against this complication.¹²² In examining 78 levels in 65 patients, they had an incidence of 13% HO, with two cases that were class III at 2 years that eventually went on to class IV (ankylosis) at 6 years. Risk factors identified included preoperative annulus ossification, bony endplate injuries during preparation for and insertion of prosthesis, malpositioning of device, and subsidence of the prosthesis.

Other notable complications that can occur include implant loosening, malposition, displacement, subsidence, early wear, and infection.¹²³ Punt et al. used a computer-generated 3D bone-implant model to determine that a reduced risk of subsidence is correlated to the implant covering >62% of the bony endplate.¹²⁴ Avoidance of undersizing may therefore reduce the risk of subsidence. Punt and colleagues also compared clinical outcomes for different revision strategies for the failure of TDA at an average of 4 years follow-up.¹²⁵ Eighteen patients underwent a posterolateral instrumented fusion without removal of the prosthesis while 21 patients had the prosthesis removed, defect filled with bone graft strut, and instrumented posterolateral fusion performed. Both procedures showed clinical improvement with no significant difference between VAS and ODI scores. Given the significant potential for injury associated with the removal and the similar outcome between the two procedures, the risk of removal should be weight against retention of device and fusion. Wear, oxidation, and, in particular, rim impingement of ultra-high molecular weight polyethylene TDRs have been observed during revision surgeries. Baxter et al. determined that severe rim impingement can increase the production of biologically relevant particles from motion-preserving lumbar TDR components,¹²⁶ while Lebl et al. found that impingement was most commonly found in extension as evidenced by metallic endplate burnishing in Prodisc-L devices.¹²⁷ Disc height distraction, anterior-posterior position, implant lordosis, and sagittal orientation all play a significant role in the occurrence of impingement and should be optimized to reduce enhanced wear and generation of particle debris.¹²⁸ Like their counterparts in hip and knee surgery, TDA wear can in turn lead to osteolysis and therefore long-term follow-up of these patients is recommended.¹²⁹

Recently Jacobs et al. published a Cochrane review of 7 randomized controlled trials on lumbar total disc arthroplasty.¹³⁰ As mentioned above, the focus of many studies has been to compare the effectiveness and safety of total disc arthroplasty to fusion. This study also found clinical outcome scores to be slightly higher in disc arthroplasty though not exceeding the clinically relevant confidence interval. Thus, adoption of total disc arthroplasty as the definitive alternative to fusion for treatment of chronic discogenic pain was cautioned against. Instead, the study advocates for further scrutiny of longer term followup data. The need is still present to demonstrate a significant advantage of disc arthroplasty over fusion to revolutionize treatment paradigms.

Nucleus Replacement

Along the spectrum of degenerative disc disease, one of the earlier signs is a loss of hydration within the nucleus pulposus. In light of this, one of the newer therapeutic alternatives to lumbar fusion is prosthetic nucleus replacement. The aim of these devices is multifold: restore intervertebral height while allowing for retention of the outer annulus fibrosus, restore the normal endplate load redistribution, recreate the intradiscal hydraulic pumping mechanism that in the native state allows for nutrient delivery and metabolic waste removal, be a minimally invasive biocompatible option, and finally permit retention of normal range of motion.

Basic requirements for implantation of a nucleus prosthesis include normal integrity of the annulus fibrosus so as to provide containment and minimize migration of the device. In addition, depending on the design of the introduction of the device, annulotomy may be required and therefore full healing potential is optimal. Contraindications include osteoporosis as well as significant degenerative changes within the endplates, as endplate arterioles must be capable of metabolic exchange. Optimal disc height is a minimum of 5 mm. In addition, these requirements also minimize the risk of subsidence after implantation.

The first nucleus replacement was designed by Dr Fernström in 1966. This was a stainless steel ball with 16 mm diameter and significant problems were encountered with prosthetic migration and subsidence.¹³¹ Since then, various models have been developed for nucleus replacement. In 1988, the prosthetic disc nucleus (PDN) was introduced by Dr Ray.¹³² This consisted of two disc cylinders oriented anterior-posterior along the plane of the disc and they were filled in situ with hydroscopic, water absorbing

gel. Clinical trials revealed a 38% revision rate leading device design modification to two transversely oriented units that are tethered by suture and contain hydrogel polymer surrounded by polyethylene jacket. In 2002, Klara and Ray published the success from a clinical trial standpoint with the PDN.¹³³ Several technique notes were made, including the use of a minimal opening in the annulus through which device units were implanted and a series of dilators to help stretch fibers without exceeding their tensile limits, in order to allow for improved healing potential. Four-year follow-up data was presented and showed a significant reduction in symptoms, Oswestry score improvement to 10% (minimal disability), mean Prolo score improvement to excellent, and disc height improvement to a mean of 1.8 mm. In review of the 423 PDNs that had been implanted since 1996, 10% had been explanted with a surgical success rate of 90%. More recently, Selviaridis et al. reported on long-term outcomes of PDN implantation in 10 patients.¹³⁴ Significant improvements in Oswestry, Prolo, and VAS scores were documented, while treated disc height was shown to increase postoperatively and be maintained. No significant modifications were found in the disc height at the level above, and lumbar spine range of motion was restricted in relation to normal but still allowed for considerable mobility.

In terms of approach to the disc for insertion of prosthetic nucleus, the traditional method has been a laminotomy as performed in a microdiscectomy to be able to access the disc space. Bertagnoli has developed the anterior lateral transpsoatic approach (ALPA) for PDN implantation.¹³⁵ Much like a lateral approach for fusion, the disc is accessed via the retroperitoneum through the psoas. An annulus flap is created to perform nucleotomy and once the device is inserted, the annulus flap is replaced and sutured in place. In his review of the use of PDN through ALPA, Bertagnoli noted lower incidence of migration.¹³⁶ In addition, he noted that use of a softer hydrogel, which absorbs 80% of its weight in water (as opposed to prior formulations which absorbed 68%), resulted in a decrease in endplate remodeling—a complication that can lead to reduced disc height and necessity for revision procedures.

An additional nucleus replacement that has recently been published is the NUBAC system.¹³⁷ This is the first articulating nucleus prosthesis that is constructed from PEEK with an inner ball/socket articulation. Balsano et al. reported on 39 patients that underwent implantation of this device through a posterior approach or extreme

lateral approach. With 2 year followup, there was a significant decrease in VAS from 71 to 14 and ODI from 58% to 14%; additionally, there was considerable symptomatic improvement in those patients with chronic low back pain.

There are a number of other nucleus replacement devices being evaluated for potential clinical use both in the United States and in Europe. Focus is also being placed on the development of injectable hydrogels that can minimize trauma associated with access to the disc and serve as a scaffold on which to develop nucleus pulposus tissue or a means by which to deliver mesenchymal cells to the nucleus pulposus for tissue engineering purposes.

CONCLUSION

In this chapter, multiple methods of surgical treatment were reviewed for the management of lumbar degenerative disc disease. Surgeons must continue to rely on level I evidence to educate patients and make clinical decisions that best suit patient desires for functional outcome in light of their medical comorbidities. Though the gold standard for surgical management remains fusion, future research will continue to focus on alternative methods of treatment that may be superior to the current standard.

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SECTION

8

Lumbar Spine 2

Yan Wang



Nonoperative Treatment of Lumbar Stenosis

Keya Mao, Peng Li

Snapshot

» Major Types of Spinal Stenosis

» Therapeutic Options for Lumbar Stenosis

INTRODUCTION

Lumbar spinal stenosis (LSS) is one of the most common reasons why patients in their middle and later years seek a consultation with a neurosurgeon or spine surgeon. Lumbar spinal stenosis is related to degeneration of the spine and usually becomes significant in the fifth decade of life and extends throughout every subsequent age group. Most patients first visit their doctor with symptoms of spinal stenosis at about 60 years of age or so. In lumbar stenosis, the spinal nerve roots in the lower back are compressed, or choked, and this can produce symptoms of sciatica-tingling, weakness, or numbness that radiates from the lower back into the buttocks and legs especially. In rare cases, LSS can produce severe persistent disabling pain and even weakness in the legs. Most cases of stenosis in the lumbar spine, however, produce pain that radiates into the legs on walking but is relieved by sitting. This is called claudication, which can also be caused by circulatory problems in the legs. Depending on the severity of the symptoms, spinal stenosis can often be managed through nonoperative treatments. This is more effective in LSS patients with mild or occasionally moderate pain.¹⁻³ Naturally, nonoperative therapy is the treatment of choice in patients without motor disturbances and/or bladder or intestinal dysfunction.⁴⁻⁷ Nonoperative treatment options include physiotherapy and exercise, epidural steroid injections, massage therapy and other analgesic or

anti-inflammatory medications, and these are usually prescribed in combination with other therapies.⁸⁻¹⁶

Lumbar spinal stenosis is typically secondary to arthritic changes in the facet joints or discs, congenital stenosis, or instability (spondylolisthesis).

MAJOR TYPES OF SPINAL STENOSIS

Foraminal Stenosis

As the nerve root is about to leave the canal through the lateral foramen, a bone spur that has already developed from a degenerating disc can press on that nerve root. This type of stenosis is sometimes termed lateral spinal stenosis, which is by far the most common form of spinal stenosis. Seventy-two percentage cases of foraminal stenosis occur at the lowest lumbar level. With this type of lumbar stenosis, the emerging nerve root is trapped. The emerging nerve root is trapped in an up down manner from a collapsed disc and its associated disc osteophyte complex.

Central Stenosis

A choking of the central canal in the lumbar area can compress the sac containing the horse's tail bundle of loose nerve filaments. Central spinal stenosis is more common at the second from the lowest lumbar spinal level and higher, and is largely caused by a bulging of the disc margin plus a major overgrowth or redundancy of a

ligament that helps protect the dura. This overgrowth is caused by segmental instability, usually from a degenerating disc between adjacent vertebrae. The ligament arises from under the flat laminae of the vertebrae and the inside part of the facet joint.

THERAPEUTIC OPTIONS FOR LUMBAR STENOSIS

Education

Providing patients with information about back anatomy causes and natural history of lumbar stenosis and advice about activity and exercise are important aspects of management. Education is helpful in setting realistic expectations for the outcome of treatment. Information may be provided by individual face-to-face contact with a physician or nurse, by an information booklet or by group sessions. Patients should be encouraged to identify activities and situations that cause discomfort and solve problems with the therapist to determine appropriate movement strategies and easing positions. Helpful advice may include items such as temporary avoidance of prolonged overhead activities, temporary avoidance of prolonged axial loading and methods of self lumbar-pelvic flexion and/or rotational stretching techniques for pain control during standing, sitting, and lying. Basic body mechanics are taught to patients with LSS, and they should be advised to change position frequently, know and respect their current limits, and pace activities such as housework and yard work. In addition, an explanation of the current concepts of pain as an “output and not an input” can help reframe the patient’s relationship with the problem and motivate them to increase their functional status. Finally, patients should be aware of the natural course of this condition. Despite the recommendations patients receive from non-medical sources, the majority of those with LSS do well over time, with their condition either remaining the same or improving with no intervention. Also, that long-term results are often no different when comparing those patients who received surgery for LSS and those who were treated nonsurgically.

Rest

In most patients with lumbar stenosis, bed rest for > 1 or 2 days should not be recommended. The primary negative consequence of inappropriate bed rest is delay in return-

ing to normal activities. In addition to delay in recovery, other potential adverse consequences of bed rest include rapid loss of muscular strength at a rate of approximately 5% per week, bone loss at a rate of nearly 1% per week, general deconditioning and increased social isolation and depression.

Physical Therapy

Daily lifestyle adjustments, back training, exercise programs to stretch, strengthening the lumbar region, and general conditioning exercises prescribed alone or together with physical therapy yield good clinical results.¹⁷⁻²⁹ Physical therapy is the foundation of nonsurgical treatment. The aim is to strengthen the abdominal and back muscles, preserve motion in the spine, and improve overall fitness. Stretching, strengthening and aerobic activity (e.g. bicycling) are usually recommended. Abdominal corsets or braces can help ease pain, but they may also weaken postural muscles, so the patient is advised not to wear a corset or brace for more than a few hours a day.³⁰ The stretching program should include stretching of the hip flexors, hamstrings, and paraspinals. The strengthening program should focus on the abdominal and gluteal musculature. A posterior pelvic tilt can be included in many of the stretching/strengthening exercises for postural education. Unloading activities are often used including traction, weight-supported treadmill walking, and water-based therapy. Other techniques used by therapists include spinal mobilization, proprioceptive neuromuscular facilitation techniques, neuromuscular massage, ergonomic training, and general reconditioning. Conditioning exercises can be designed to avoid pseudoclaudication. Walking on an incline is often better tolerated than level walking. Stationary biking is usually comfortable.

Swimming is also a good alternative; sidestroke is sometimes better tolerated than breaststroke or freestyle that requires lumbar extension.³¹ Physical therapy includes both passive and active treatments. Passive treatments help relax the body. They also prepare the body for therapeutic exercise, which is the active part of physical therapy. Physical therapist can give passive treatments such as deep-tissue massage: this technique targets chronic muscle tension in the lumbar spine that perhaps builds up as a result of daily life stress. The therapist uses direct pressure and friction to try to release the tension in the soft tissues (ligaments, tendons, muscles).

Hot and Cold Therapies

By using heat, the physical therapist seeks to get more blood to target the area because an increased blood flow brings more oxygen and nutrients to that region that helps the body to heal. Cold therapy slows the circulation, helping to reduce inflammation, muscle spasms, and pain. Your physical therapist will alternate between hot and cold therapies.³²⁻³⁴

Exercises

Exercises may include the use of an exercise bicycle and/or brief walks. Walking is a suitable exercise for spinal stenosis patients. Swimming is also an ideal exercise because it exercises all the back muscles in a safe, supportive environment. The water supports the weight well, which means that there is less weight on the patient's back. One could also combine walking and swimming and do some water walking. Gentle stretches that relieve the pressure on nerves are a great help too. Because spinal stenosis decreases the space that the spinal cord and nerve roots go through, exercises that open up that space are recommended. Generally, flexion exercises are helpful in alleviating the symptoms of spinal stenosis. Although a suitable program of spinal stenosis exercises may be helpful in the hands of a good physical therapist, it is not curative. Even though stenosis exercises are not a cure, however, it is very important for patients to remain active and not additionally debilitated from inactivity. Therefore, appropriate spinal stenosis exercises are a key part of any treatment program. Progressive exercise may help increase lumbar-pelvic muscular stabilization and maintain better posterior pelvic tilt. It may also improve cardiovascular conditioning and other factors that enhance soft tissue function. Studies on exercise treatment particularly emphasize the importance of flexion exercises and recommend the addition of general conditioning exercises.³⁵⁻³⁷

Epidural Injections

Epidural interventions are one of the most commonly performed interventions for managing LSS.³⁸⁻⁵⁸ The use of steroid injections is based on the belief that pain symptoms result from inflammation at the interface between the nerve root and the compressing tissues.^{59,60} The purpose of injecting corticosteroids is to reduce inflammation, and these injections are frequently combined with local anesthetics for pain relief. In addition to therapeutic

treatment, epidural steroid injections are also frequently used for diagnostic purposes.⁶¹ There are three major types of epidural steroid injections performed for LSS: the traditional translaminar injection, the caudal injection, and the transforaminal injection.⁶²⁻⁶⁸ However, transforaminal epidural injections are also associated with substantial risk compared to either caudal or interlaminar epidural injections.⁶⁹⁻⁸¹ Although there is no consensus regarding frequency, most practitioners recommend that individuals not receiving substantial relief with the first injection undergo up to two repeat injections at 2–4-week intervals. A number of trials have looked at the efficacy of steroid injections. Although there are mixed results, the majority of studies have unfavorable long-term results. Rosen et al.⁸² did a retrospective study of 40 patients with LSS who received translaminar epidural injections; 60% of those patients reported relief at 2 months and only 25% had relief at 8 months. Cuckler et al.⁸³ performed a prospective randomized evaluation of a translaminar epidural injection and found that only 2 of 41 patients had significant relief (>75%) at long-term follow-up. Buenaventura et al.⁸⁴ in a systematic review of therapeutic lumbar transforaminal epidural steroid injections, evaluated four randomized trials⁸⁵⁻⁸⁶ based on Cochrane musculoskeletal review group criteria, with criteria of short-term relief as <6 months and long-term relief as >6 months. They showed Level II-1 evidence for short-term relief and Level II-2 for long-term relief in managing chronic low back and lower extremity pain. Normally, patients were administered the first injection by the translaminar or caudal route. The second injection was administered at the level of the most significant thecal sac compression by the transforaminal (specifically epidural and not extraforaminal or nerve root sheath injection) route. The third was administered when needed, according to the physician's discretion.⁸⁷

Ultrasonography is effective for guiding caudal epidural injections. Ultrasound guidance is a rapid and safe means of ensuring that the injection is performed into the epidural space. The lower risk of postlumbar puncture syndrome and the ease of execution may make caudal epidural injection a good method for treatment at the rheumatologist's office.⁸⁸

Massage Therapy

Massage therapy in various forms has been widely used in the treatment of back pain for many years. Massage therapy takes many forms, including classical Swedish,

deep-tissue massage, acupuncture massage, friction massage, myofascial release, and other variations.

Transcutaneous Electrical Nerve Stimulation

Transcutaneous electrical nerve stimulation (TENS) has been used for pain relief for >30 years. As originally conceived, TENS was a noninvasive technique of peripheral nerve stimulation based on the premise that counter stimulation of the appropriate nerve fibers would alter pain perception. The gate-control theory of pain provided the initial theoretical framework for TENS development. As suggested in animal models, high-frequency, low-intensity TENS was believed to stimulate large afferent nerve fibers that activate inhibitory neurons at the local dermatomal spinal cord level, resulting in the inhibition of smaller sensory nociceptive fiber inputs.

Acupuncture and Electroacupuncture

Acupuncture is a centuries-old therapy, rooted in East Asian medicine, which has been increasingly adopted and adapted by Western practitioners. More than 1 million Americans are treated with acupuncture annually for a variety of musculoskeletal conditions, including fibromyalgia and low back pain. Acupuncture and pressure point massage are mildly helpful for LSS, and the benefits last for up to 1 year. Massage appears to be most effective when combined with exercise, stretching, and education.⁸⁹

Electroacupuncture of spinal nerve roots employs a selective spinal nerve block technique for inserting acupuncture needles. After inserting two needles as close as possible to the relevant nerve root under X-ray fluoroscopy, low-frequency electroacupuncture was performed using the needles as electrodes. Under X-ray fluoroscopy, two acupuncture needles were inserted as close as possible to the relevant nerve root, as determined by subjective symptoms, and X-ray, magnetic resonance imaging (MRI), and low-frequency electroacupuncture stimulation (10 Hz, 10 minutes) were performed. Patients received 3–5 once-weekly treatments and were evaluated immediately before and after each treatment and 3 months after completion of the treatment.^{90,91} The relevant nerve root was determined from symptoms, physical findings, and imaging data (plain X-ray, MRI). Using a procedure similar to that used for spinal nerve root block, with the patient in the prone position, two disposable

acupuncture needles (90 mm long, 0.25 mm in diameter, Seirin Co., Shizuoka, Japan) were inserted as close to the relevant nerve root as possible under X-ray fluoroscopy. Low-frequency electroacupuncture was then conducted using the two needles as electrodes (stimulation frequency 10 Hz, stimulation time 10 minutes, stimulation strength at a tolerable level for the patient). The verification of the proximity of the needles to the relevant nerve root was performed by approximate positioning using X-ray and comments by patients where stimulation could be felt in an area supplied by the damaged nerve. Treatment was performed once a week. If symptoms were found to have been completely resolved 1 week after the previous treatment, that day was taken as the final day of treatment, with five being the maximum number of treatments.

Nonopioid Analgesics and Nonsteroidal Anti-inflammatory Drugs

For LSS, medications are not the initial therapy physicians should consider. According to a comprehensive review, at best drugs relieve only about 30% of chronic pain. In older patients, pain medications increase the risk of falls, cognitive deficits, constipation, bladder dysfunction, and adverse drug interactions. Medications are useful but should not be the primary intervention for spinal stenosis.⁹²

Anti-inflammatory medication (such as aspirin or ibuprofen) may be helpful in treating spinal stenosis. Some physicians recommend a multiple B-complex vitamin with 1,200 µg of folic acid daily, but this has not been substantiated in the medical literature as an effective treatment for stenosis. In patients with less severe symptomatology, nonsteroidal anti-inflammatory drugs (NSAIDs) were administered for a 4–6 week period of time and occasionally repeated. Most patients with significant radiculopathy were administered one course of oral corticosteroids on a 7-day tapering schedule. Acetaminophen is the first-line therapy because of its high safety profile. Nonsteroidal anti-inflammatory drugs provide similar analgesia but have significant gastrointestinal and renovascular adverse effects.^{93,94}

Nonsteroidal anti-inflammatory drugs have anti-inflammatory and pain relief properties that make them attractive for the treatment of spinal stenosis, but are equally efficacious compared to acetaminophen, which only provides pain relief.⁹⁵ Cyclo-oxygenase (COX)-2 selective agents had been recommended for older individuals because of fewer serious gastrointestinal side effects. However,

recent evidence of increased cardiovascular risk especially associated with long-term use in higher-risk individuals makes these agents unattractive in patients with spinal stenosis.⁹⁶ Narcotics may be helpful when used for short periods on a regular basis in individuals with severe pain, including radicular pain associated with spinal stenosis that is not controlled by NSAIDs or acetaminophen. For patients with persistent symptoms, short-acting, and long-acting opioids are often used despite very limited evidence of efficacy. Few authors have compared the risks and benefits of opioids with other medications when used on a continuous basis for a longer period of time, especially in older individuals who may be at a greater risk of experiencing side effects.^{97,98}

Muscle Relaxants

Muscle relaxants make less theoretical sense, given the degenerative nature of LSS, but again there are no trials demonstrating the superiority of other listed medications.⁹⁹ Although the precise anatomic source of lumbar stenosis is frequently ill defined, muscle sprain or strain is believed to be responsible in many patients. All muscle relaxants provide similar short-term improvements in pain and function, but there is no unequivocal data to support their long-term use to treat chronic low back pain. Sedation is a common adverse effect and continuous use of benzodiazepines and carisoprodol (Soma) carries the risk of dependency.¹⁰⁰ Given the underlying degenerative process thought to be associated with the development of symptomatic spinal stenosis, the use of muscle relaxants (such as diazepam or cyclobenzaprine) in spinal stenosis makes less inherent sense, although there is no evidence arguing that the relative risks and benefits favor other agents. For patients without severe pain, muscle relaxants and narcotics offer few advantages and have more side effects.¹⁰¹

Antidepressants

Antidepressant therapy is appropriate for patients with depressive symptoms that accompany the chronic pain, but its value for patients who are not depressed is unproven. When used, antidepressants with combined serotonergic-noradrenergic effects, such as the tricyclic antidepressants (TCAs), have more consistent antinociceptive effects than agents that only affect serotonergic systems. Finally, a randomized study of nasal calcitonin was ineffective compared with a placebo for patients with spinal stenosis. This study represents what will hopefully be an increased number of high-quality controlled trials of treatments

for this disorder.^{102,103} Tricyclic antidepressants are an option in the algorithm to manage subacute or chronic lower back pain. Nortriptyline was selected for patients with sicca symptoms. The dose was increased weekly by 10 mg until the patient was satisfied with the level of pain control or side effects were noticed. The TCA dose in patients with clinical improvement ranged from 10 to 100 mg. More than half (11, 55%) of the patients who reported clinical improvement stayed on the initial dose of 10 mg daily of either amitriptyline or nortriptyline, with good results.

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Lumbar Spinal Stenosis: Open Operative Treatment

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Snapshot

- » Pathophysiology
- » Clinical Presentation and Entities
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- » Open Operative Treatment using Lumbar Stenosis: Surgical Techniques
- » Authors' Preference
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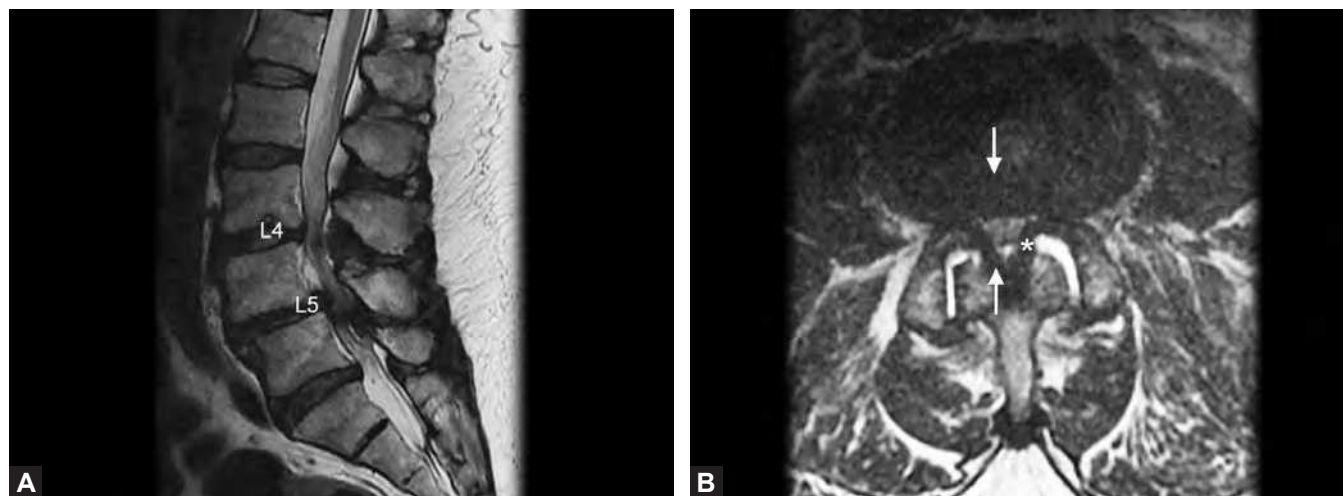
INTRODUCTION

Lumbar canal stenosis is an established spinal pathology and the first description of the narrow spinal canal dates back to 1803, when it was described by Antoine Portal.¹ However, the most advances in the diagnosis and management of spinal stenosis have taken place in last 50–60 years. Etiologies for lumbar canal stenosis vary; however, it can generally be grouped into degenerative, congenital, or metabolic disorders. Degenerative spinal canal stenosis is the most common pathological process resulting in the critical narrowing of the spinal canal, which compresses the neural elements. Degenerative stenosis is attributed to the degenerative changes in facet joints, ligamentum flavum, and intervertebral discs. Congenital spinal stenosis occurs because of growth disturbances of posterior elements, resulting in abnormal anatomy and deformities, and can result in symptomatic presentation early in the life.² Bone dysplastic disorders, such as achondroplasia, can result in spinal stenosis because of narrow and short pedicles and medialized facets.³ Some metabolic and storage disorders like Paget's disease and Morquio's syndrome can result in abnormal accumulation of undegraded substances in tissues resulting in narrowing of the space available for the neural elements. In this chapter, we will focus

predominantly on degenerative lumbar spinal stenosis. The purpose of this chapter is to review the pathophysiology, clinical features, indications, surgical techniques, and outcomes for the open surgical management of lumbar spinal stenosis.

PATHOPHYSIOLOGY

The degenerative process generally starts with disc dehydration, disc height loss, and bulging of disc and ligamentum flavum in the canal and, eventually, formation of disc-osteophyte complexes that decreases the volume of the spinal canal.⁴ Loss of normal disc function results in abnormal stress transfer and concentration at facet joints, which causes the thinning of the facet cartilage and subsequent osteophyte formation. With progressive incompetence of the facet joint capsule and disc degeneration, segmental spinal instability can occur and result in varying degrees of “olisthesis” (slippage) of one vertebra in relationship to another. This progression of degenerative changes can result in characteristic anatomic areas of stenosis, which include the central canal, the lateral recess, and neuroforaminal zone. Along with direct compression, local inflammation, neural ischemia, and neuritis are all additional contributors to the pathophysiology of the disease.



Figs. 80.1A and B: (A) Sagittal and (B) axial T2-weighted magnetic resonance imaging (MRI) of the lumbar spine demonstrating central stenosis. Notice the more sagittally oriented facet joint and hypertrophy of the inferior articular facet (asterisk) of the superior vertebra will result in central stenosis (arrows). Notice the presence of high-intensity fluid within the facet joints bilaterally suggestive of fluid and potential facet incompetence, which is confirmed by the presence of subtle grade 1 spondylolisthesis on the sagittal MRI at L4-L5.

Central Stenosis

Anatomically the inferior articular facet/process of the cephalad vertebra lies posteromedial to the SAP of the more caudal lumbar vertebra. Therefore, hypertrophy of the inferior articular facet will classically result more in central spinal stenosis (Figs. 80.1A and B). Classically these patients will present with symptoms of multiple root compression and neurogenic claudication.

Lateral Recess Stenosis

Lateral recess stenosis is also known by several other terms, which include “subarticular stenosis” and “entry zone stenosis.” Anatomically, the lateral recess lies just ventral to the superior articular facet/process (SAF/SAP). Therefore, hypertrophy of the SAF typically results in lateral recess stenosis (Figs. 80.2A and B). Classically these patients will present with symptoms of single root compression and radicular symptoms.

Neuroforaminal Stenosis

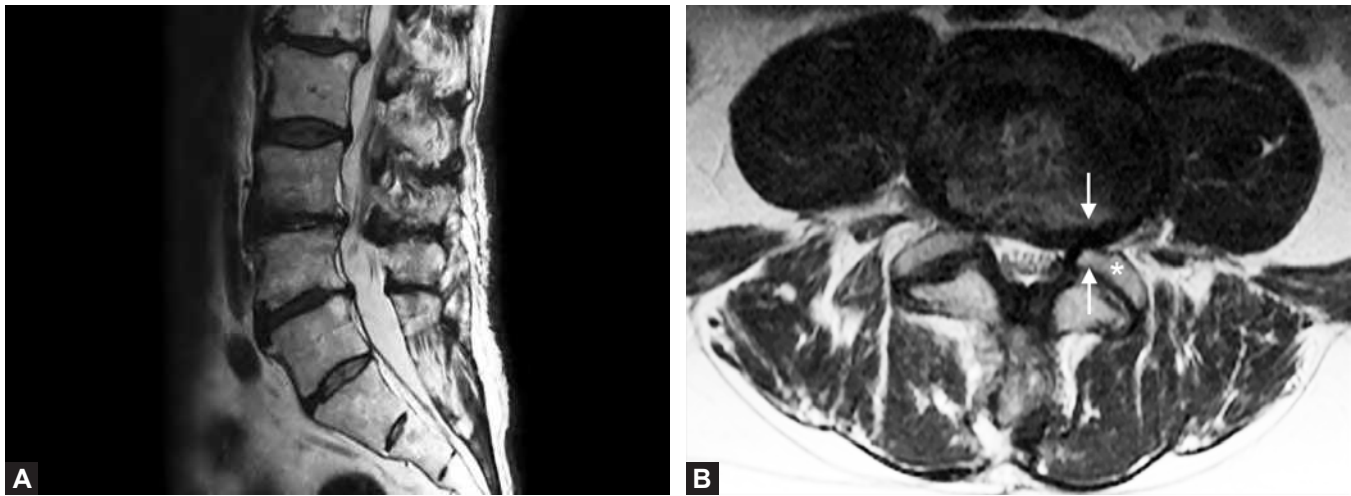
Anatomically the neuroforamen is bound anteriorly by the posterior aspect of the vertebral body and intervertebral disc, posteriorly by the pars, and superiorly and inferiorly by the corresponding pedicles. Therefore, the most common causes of neuroforaminal stenosis include advanced disc degeneration and progressive collapse of the

intervertebral disc space resulting in the so-called “up-down stenosis” (Fig. 80.3). However, extruded discs migrating into the neuroforamen and pars defects can also result in neuroforaminal stenosis.

CLINICAL PRESENTATION AND ENTITIES

The clinical symptoms for lumbar spinal stenosis vary from patient to patient and, as discussed above, are related to the area of neural compression. Lumbar central stenosis typically causes the symptoms of neurogenic claudication, while lateral recess and neuroforaminal compression classically result in single nerve root compression (radiculopathy). Classic neurogenic claudication symptoms are described by the patients as numbness, tingling, weakness, and leg heaviness typically reported in the posterior buttock radiating down the posterior lateral thigh.⁵ This should be differentiated from pain radiating in a more specific dermatomal location raising the concern for a concomitant nerve root compression.

Neurogenic claudication is caused by direct compression of the neural vascular supply, which leads to its clinical manifestations. The incidence is predicted to increase as the lifespan of the general population increases. Due to improvements in health care and life expectancy, there will continue to be a larger population of active elderly individuals who are predisposed to developing lumbar



Figs. 80.2A and B: (A) Sagittal and (B) axial T2-weighted magnetic resonance imaging of the lumbar spine demonstrating lateral recess or subarticular zone stenosis. Notice the more coronally oriented facet joints and hypertrophy of the superior articular facet (asterisk) of the inferior vertebra results in lateral recess, or subarticular zone stenosis (arrows). The central canal remains relatively less involved.



Fig. 80.3: Parasagittal T1-weighted magnetic resonance imaging demonstrating foraminal zone stenosis (arrowhead). Notice that loss of the normal perineural foraminal fat at the stenotic level at L5-S1.

stenosis, which is a major cause of impaired quality of life and pain. Up to 25% of the general population has lumbar stenosis over the age of 50 years.

When treating lumbar stenosis, one must have a thorough understanding of the diagnosis, evaluation and pathologic anatomy. As discussed in the previous chapter a course of appropriate nonoperative management should be the first line of treatment. When indicated, operative treatment has been shown to produce significant, long-lasting outcomes.

Table 80.1: Differential diagnosis for lumbar stenosis.

- Peripheral artery disease (vascular claudication)
- Leriche's syndrome
- Hip osteoarthritis
- Lumbar spondylosis
- Diabetic peripheral neuropathy

A thorough clinical history should be taken. Often times, the duration, inciting factors, and pain location can help differentiate lumbar stenosis from other disease processes (Table 80.1). In order to not miss concomitant pathology and to help ascertain where the compressive pathology is affecting the neural elements, a complete motor, sensory, and reflex examination should be undertaken. Attention should be paid to previous scar, sagittal, and coronal alignment. In addition, close attention should be given to the age of the patient and comorbidities, as these affect patient outcomes and risk for complications with surgical treatment.

Neurogenic claudication and back pain caused from lumbar stenosis must be differentiated from vascular claudication or other common diagnoses that cause leg pain (Table 80.1). A classic complaint in patients with lumbar stenosis is posterolateral buttock and leg pain with characteristics of burning, paresthesias, heaviness, or easy fatigue. The pain is mechanical, but unlike vascular pathology, riding a bike or walking uphill will not cause symptoms because the cross-sectional area of the central canal

and neuroforamina is increased with the forward flexion posture. Therefore, neurogenic claudication pain is exacerbated with back extension and alleviated with lumbar flexion, the so-called “shopping cart sign.” Walking downhill is worse with lumbar stenosis, the opposite of vascular claudication.

Vascular claudication due to peripheral artery disease is often accompanied by other physical examination findings. There are skin changes (edema and decreased hair) and diminished peripheral pulses. The symptoms are also relieved by cessation of activity, but forward flexion does not improve the symptoms. Forward flexion and sitting alleviate symptoms in lumbar stenosis due to opening the spinal canal. Vascular disease due to proximal aortoiliac occlusive disease (Leriche’s syndrome) should be considered. Leriche’s syndrome has the triad of buttock claudication, atrophy of the gluteal muscles, and impotence.

Hip arthritis typically presents as anterior groin pain. Typically, this pain can be reproduced with internal and external rotation of the hip, and often times has start up pain and pain at night described as a “tooth ache.” Similar to lumbar degenerative disease, hip arthritis may benefit from localized steroid injections. In this way, a fluoroscopically guided hip injection can be used for diagnostic and therapeutic purposes.

Diabetic or idiopathic peripheral neuropathy can also cause symptoms of leg pain. This pain is usually unrelated to activity and typically involves both lower legs in a stocking glove distribution.

A full discussion of the examination of the patient with lumbar spinal stenosis is beyond the scope of this chapter; however, it can vary to a large degree from patient to patient and is typically unremarkable. Patients may prefer a forward flex posture with aggravation of their symptoms with lumbar extension. While pain and or numbness can be common, motor weakness is relatively uncommon, and typically reflexes are normal. However, in patients with severe stenosis reflexes can be diminished. Provocative tests, such as the straight leg raise is typically negative in degenerative spinal stenosis. Questions in regard to bowel and bladder dysfunction should also be elicited.

It should be noted that a careful upper extremity examination should be undertaken in all patients with lumbar stenosis, because upper motor neuron (UMN) signs such as lower extremity hyperreflexia, clonus, and Babinski’s signs can be absent in patients with severe lumbar stenosis and may only be identified through a careful history and potential presence of upper extremity UMN signs such



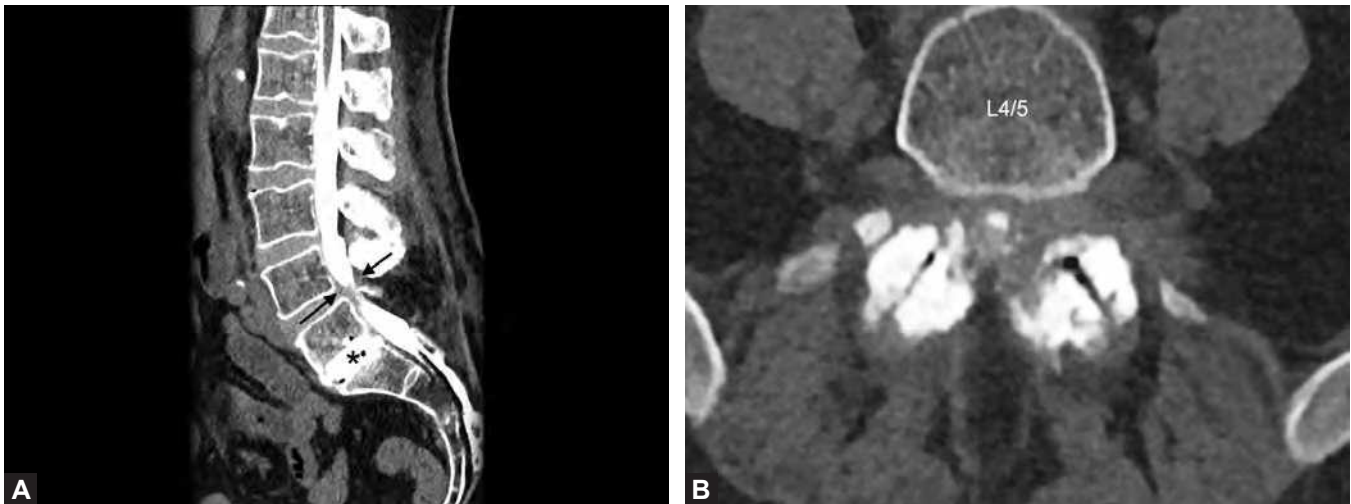
Figs. 80.4A and B: (A) Extension and (B) flexion standing lateral radiographs demonstrate the presence of a spondylolisthesis.

as Hoffman’s signs and upper extremity hyperreflexia. In these patients, advanced imaging of the cervical spine should be considered, and depending on the findings, may warrant addressing the cervical stenosis prior to any lumbar interventions.

IMAGING

Imaging should begin with upright anteroposterior, lateral and flexion–extension views of the lumbar spine. Stress views or lumbar spine flexion/extension views (Figs. 80.4A and B) help in defining any evidence of instability or spondylolisthesis, as the presence of a spondylolisthesis could warrant fusion of the unstable segments in addition to the decompression. If there is scoliosis or concerns of a significant sagittal plan deformity, a full-length standing scoliosis film will give the surgeon an idea of the sagittal and coronal alignment of the spine. Assessment of the pelvic incidence, pelvic tilt, sacral slope and facet orientation at the involved level is also advised if there is consideration of more than just a decompression procedure.

Magnetic resonance imaging (MRI) is the diagnostic modality of choice to give further detail into the degrees of stenosis. The nerve roots tend to sediment in the posterior half of the sac on a supine MRI axial image, and the absence of normal sedimentation of the roots in the presence of central canal stenosis, a “sedimentation sign,”^{6,7} is reported to correlate with central stenosis in 54% of the patients. It is reported to be positive in 82% of cases with dural sac cross-sectional area of <80 mm.⁷ In the case of



Figs. 80.5A and B: (A) Sagittal and (B) axial computed tomography (CT) myelogram demonstrating adjacent segment stenosis at L4-L5 (arrows) above a previous decompression and fusion at L5-S1. Notice CT myelogram defines the presence of the interbody fusion (asterisk) and the extent of the bony decompression on the sagittal and axial images.

revision surgery, the use of MRI with gadolinium can help differentiate scar from recurrent disc material.

The disadvantage to MRI is high rate of false-positive degenerative changes. In an MRI study of 67 asymptomatic individuals, Boden et al.⁸ reported that in the patients aged 60 years or older, the findings were abnormal on about 57% of the scans; 36% of the subjects had a herniated nucleus pulposus, while 21% had spinal stenosis. There was degeneration or bulging of a disc at least one lumbar level in 35% of the subjects aged between 20 and 39 years and in all but one of the 60- to 80-year-old subjects.

A computed tomography (CT) myelogram is beneficial in patients who are unable to obtain an MRI due to medical or device-related issues such as cardiac pacemaker. A CT myelogram may also be considered to be the advanced imaging of choice in patients with spinal implants, where implant-related artifact can degrade the quality of the MRI images and identification of the trajectory, location, and position of the implants is required. A CT myelogram can also be beneficial in patients with significant spinal deformity and in revision cases where assessment of adjacent level disease or residual stenosis due to bony compression is suspected (Figs. 80.5A and B).

Because radiographic imaging demonstrating the presence of degenerative changes is very common in both MRI and CT myelogram, determination of the pain generator can be difficult. Due to this uncertainty, it is vital to correlate the information from clinical examination find-

ings, patient complaints, and imaging in order to prescribe the best treatment to patients with lumbar stenosis. Once the diagnosis of symptomatic spinal stenosis has been made, the advanced imaging is a preoperative to help assess the location and extent of stenosis.

INDICATIONS

Despite the fact that evidence supporting the nonoperative or conservative treatment for stenosis is scant, and a systematic review study by Ammendolia⁹ also failed to provide any moderate-to-high-quality evidence for the same, it is the authors' opinion that surgical management should be considered only after all other nonoperative alternatives have been maximized. Surgery for lumbar stenosis is indicated when there is a failure of conservative treatment and a significant effect on the patient's quality of life, and when other pathology has been ruled out. Lumbar epidural steroid injections, nonsteroidal anti-inflammatory drugs, physical therapy and activity modification are the mainstay of conservative treatments for lumbar stenosis and should be attempted first. The natural history of lumbar stenosis is a gradual onset of symptoms, and if there is rapid progression of symptoms, then other etiologies should be considered.

Decompressing the stenotic area is a proven and effective surgical treatment for lumbar stenosis. There are no absolute contraindications to surgery but a thorough history and physical examination should be undertaken with

careful attention to comorbidities that could cause perioperative complications. Once a clinical and radiographic diagnosis is confirmed, there are different surgical options and considerations for lumbar stenosis.

The principle of surgical treatment is to fully decompress the spinal canal in the areas of stenosis, whether it is the central, lateral recess or neuroforaminal zone. It is important when counseling patients with neurogenic claudication or radicular pain from lateral recess stenosis, that back pain due to disc degeneration or facetogenic pain may not be alleviated with decompression.

■ OPEN OPERATIVE TREATMENT USING LUMBAR STENOSIS: SURGICAL TECHNIQUES

General surgical considerations include obtaining a complete decompression while preserving motion segments. It is of utmost importance to preserve the stability of the spine when fusion is not planned. However, in the presence of deformity, segmental instability or iatrogenic instability, fusion with or without instrumentation should be considered.

Laminectomy with or without Foraminotomy

Open total laminectomy is a mainstay of treatment for lumbar central and lateral stenosis. For the standard midline posterior approach, the patient is positioned prone. A Jackson or Andrews table can be used as it allows the abdomen to hang free, which decreases intra-abdominal pressure and thus decreases epidural venous pressure and surgical site bleeding. Extension of the hips will recreate the physiologic stenosis allowing the surgeon to directly palpate appropriate decompression of the stenosis. The planned level can be established with an anteroposterior and lateral fluoroscopic view prior to incision. The incision should be centered around the planned levels of decompression based on pre-operative imaging. All radiographic areas of stenosis that correlate to the physical examination should be decompressed.

For a standard open posterior approach, the midline incision is carried down to the supraspinous ligament over the spinous processes. Electrocautery is used to subperiosteally dissect down onto the lamina. For a total laminectomy, the supraspinous ligament and spinous process can be removed. In order to preserve the supraspinous and interspinous ligaments above and below the planned

decompression levels, only one inferior half of these spinous processes are removed at these levels.

A curved curette can be used to detach the ligamentum flavum. Extreme care should be taken when dissecting down the lamina in order to avoid violation of the facet capsule. If necessary for complete decompression, up to 50% of the facet joint and lateral part of pars interarticularis can be removed for surgical decompression without causing any instability.¹⁰ Over resection of the pars can also lead to fracture and potential instability and should be avoided, if possible.

Hemilaminectomy with or without Foraminotomy

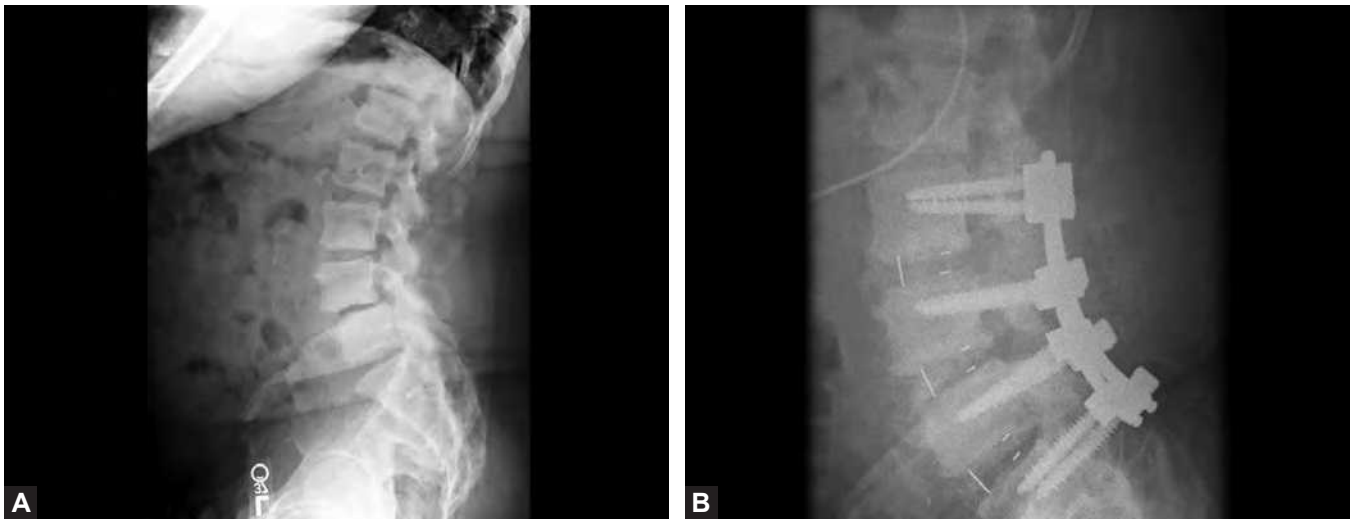
A fenestration or keyhole hemilaminectomy technique can be used for decompressions as well. In fact, in patients with unilateral single lateral recess stenosis without significant degree of central stenosis, a unilateral hemilaminectomy may be considered the procedure of choice. By definition, hemilaminectomies have the added benefit of preserving the midline ligamentous structures, more specifically the spinous process and the supra- and interspinous ligaments and, theoretically, have a lower risk for resulting segmental instability and adjacent segment disease. Furthermore, in some cases, bilateral hemilaminectomies or “box outs” can be used for patients with central stenosis.

In the hemilaminectomy, each planned level is sequentially decompressed by removing half of the inferior lamina for the cephalad vertebral body and the superior half of the caudad lamina on the symptomatic side. The ligamentum flavum attaches on the anterior aspect of the superior lamina and the superior aspect of the inferior lamina. Removing the superior hemilamina allows the release of the attachment site of the ligamentum flavum.

In the case of central stenosis, the central and contralateral stenosis can be addressed through either bilateral hemilaminectomies or through a unilateral approach by “airplaning” the operating table away from the operative side and decompressing the contralateral side while leaving the spinous process and interspinous ligaments intact. Although technically more demanding, this technique has been shown to be effective to achieve decompression without creating instability.

Foraminotomy

Foraminotomies are typically not preformed alone and are included as part of the laminectomy and hemilaminectomies.



Figs. 80.6A and B: (A) Preoperative lateral standing radiographs demonstrating the presence of spondylolisthesis in the presence of spinal stenosis. (B) Postoperative lateral standing radiographs demonstrating spinal fusion with posterior pedicle screw fixation and lumbar interbody fusion with postoperative reduction of the spondylolisthesis.

Direct foraminal decompression is performed by following the exiting root through the lateral recess out into the neuroforamen. This may require resecting the leading edge of the inferior lamina. The pars can be undercut utilizing the curved foraminotomy Kerrison Rongeurs that are designed to allow the surgeon to pass the Kerrison punch into the foramen and resect the ventral aspect of the pars, which makes up the posterior aspect of the neuroforamen. It is important during this maneuver to remain dorsal to the nerve root and care should be taken to avoid excessive pars resection.

Although controversial and beyond the scope of this chapter, indirect foraminal decompression through restoration of intervertebral disc height to address “up-down stenosis” has been advocated by some surgeons. Unfortunately, currently this can only be performed through interbody fusions either as an anterior lumbar interbody fusion, direct lateral interbody fusion, or posterior or transforaminal interbody fusion, depending on surgeon preference, location of pathology, and patient habitus and anatomy.

Spinal Fusion

Special consideration to fusion should be given in certain circumstances. If there is degenerative spondylolisthesis or scoliosis, signs of instability, or if the amount of decompression destabilizes the spine, then uninstrumented or instrumented fusion is recommended (Figs. 80.6A and B). On the preoperative MRI, facet cysts, fluid in the facets

(see Fig. 80.2B), and facet synovitis are signs suggestive of segmental instability.

Intraoperative assessment of the possible unstable level can be performed by gross assessment of the motion at the level. Preoperative flexion and extension films can document dynamic instability if greater than 3 mm of translation. Occasional on a revision or primary lumbar decompression, >50% of the facet or pars may need to be removed for adequate decompression. In such cases, fusion should be performed to prevent an iatrogenic instability.

A classic study by Herkowitz et al. demonstrated that inter laminar fusion in addition to decompression provided superior clinical results in patients with lumbar spinal stenosis and degenerative spondylolisthesis. The superior results of fusion in patients with spondylolisthesis as compared to stenosis have been confirmed in Spine Patient Outcomes Research Trial (SPORT) as well.¹¹ Instrumentation has also been shown to improve fusion rates. Instrumented fusion has thus been the treatment of choice when performing a fusion, although there is lack of evidence of a significant cost-effective benefit.

However, the inclusion of fusion with and without instrumentation in patients with stenosis without deformity and/or segmental instability is more controversial and unclear. Bae¹² analyzed the US nationwide data and reported that the trend of adding fusion to decompression procedure is increasing and that 26% of decompression surgeries in 2009 were combined with a fusion procedure for symptomatic stenosis without any evidence of slip.

Forsth¹³ reported the role of fusion in 5,390 symptomatic stenotic patients with a 2-year follow-up and concluded that the outcomes were similar for decompression as compared to decompression and fusion and that the addition of fusion to decompression was not associated with an improved outcome.

AUTHORS' PREFERENCES

It is the opinion of the authors of this chapter that whenever possible a decompression alone to address the area of symptomatic stenosis should be attempted. In case of preoperative evidence of instability, presence of deformity or an iatrogenic stability occurring due to the need for resection of supporting structures, fusion should be included. The inclusion of instrumentation is not required in all the fusion cases. However, in our experience, instrumentation improves the ability to restore a more physiologic coronal and sagittal alignment, while increasing fusion rates. Routine use of fusion procedures for patients with stenosis without any instability or deformity should be avoided.

OUTCOMES

There is good evidence to support that surgery for lumbar spinal stenosis is effective in relieving symptoms. Multiple studies have been performed; however, currently the SPORT study by Weinstein et al.¹⁴ provides level 1 evidence that surgery for the treatment of spinal stenosis is a viable and proven option when appropriate nonoperative care has failed. Furthermore, the results of the SPORT data at a follow-up of 4 years also demonstrate that the benefits and the quality-adjusted life year gained with surgery remains cost-effective.¹⁵

More specifically the SPORT study compared surgery versus conservative treatment in a multicenter study of patients having at least 12 weeks of symptoms and studied the outcomes at 6 weeks, 3, 6, 12, and 24 months. Of 289 surgically treated and 365 conservatively treated patients, patients who underwent surgery demonstrated significantly greater improvement in all primary outcomes than did patients who were treated nonsurgically at 2-year follow-up. The superior results of surgery were most pronounced at 3-month postoperative follow-up.¹⁴

When the study analyzed factors affecting the treatment outcome, Weinstein concluded that other than smoking, all analyzed subgroups that include at least 50 patients improved significantly more with surgery than with nonoperative treatment. This study showed that patients

with a baseline Oswestry Disability Index (ODI) ≤ 56 , patients who are nonsmokers, patients with the presence of neuroforaminal stenosis, patients with the predominance of leg pain, patients not lifting at work and patients with the presence of a neurologic deficit were all associated with greater therapeutic benefit with surgery as compared to the conservative treatment.¹⁶ Furthermore, the superior efficacy of surgery compared to nonoperative treatment was established at 4-year follow-up as well with regard to pain and function.¹⁵ In a cost-effective analysis as a part of SPORT, Tosteson¹⁷ studied 634 patients with spinal stenosis of which 394 (62%) underwent surgery and reported that the surgery is a cost-effective management tool as compared to other interventions for these patients.

COMPLICATIONS

Complications for open treatment of lumbar stenosis are not uncommon. Risk of mortality increases with age and the number of comorbidities. In general, the risk of mortality is $<1\%$, but in octogenarians there is mortality rate as high as 3% .^{10, 11}

Dural tear is a common complication of surgery for lumbar stenosis. Minimal invasive surgery has a slightly higher risk of incidental dural tears. This complication can lead to an increase in hospital stay, pulmonary and skin complications due to bed rest, and neurologic decline. There is a wide range of incidence in dural tears reported in the literature, from 1% to 17% . This complication is higher with decompression for lumbar stenosis, increasing age, and revisions. Persistent pseudomeningocele formation can lead to drainage, infection, and direct compression of neural elements. Adjacent level disease or reoccurrence of stenosis are some other complications associated with poor surgical outcome and patient dissatisfaction.

Kim¹⁸ analyzed the surgical outcome in 11,027 patients operated for stenosis without spondylolisthesis and reported the cumulative reoperation rate after surgery to be 4.7% at 3 months, 7.2% at 1 year, 9.4% at 2 years, 11.2% at 3 years, 12.5% at 4 years, and 14.2% at 5 years. The adjusted reoperation rate was not found to be different between decompression and fusion surgeries. The calculated reoperation rate was expected to be 22.9% at 10 years.

RECENT ADVANCES

A facet sparing decompression technique using the flexible microblade shaving system is reported to provide similar outcome as compared to the conventional

decompression techniques while sparing the facet to a greater extent with lesser blood loss and surgical time.¹⁹ Interspinous distraction techniques also offer outcome similar to decompression procedure with fewer complications related to the surgical procedure. However, the revision surgery rate is reported to be higher than the decompression or fusion surgeries.²⁰

CONCLUSION

Lumbar stenosis is becoming a more frequently recognized cause of neurogenic claudication and leg pain significantly affecting patient's quality of life. An attempt at nonoperative management is the first line of defense and there is good evidence that many patients can obtain significant relief. Once failing, conservative treatment decompression surgery has been shown to be a valid option to relieve symptoms and improve patient's quality of life. The surgery is not without risk of significant complications, and a thorough preoperative discussion is necessary in order to educate patients on the disease process and provide realistic expectations of the chosen treatment strategy.

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Lumbar Interspinous Implants

Dennis S Meredith, Alan S Hilibrand

Snapshot

- » Biomechanical and Imaging Studies
- » Clinical Results
- » Complications
- » Cost-Effectiveness

INTRODUCTION

Reportedly, the first use of interspinous spacers dates back to the 1950s, when Dr Fred Knowles began placing metal “plugs” between the spinous processes of patients with spinal stenosis.¹ This practice did not persist due to frequent displacement of the implant requiring removal. Nonetheless, the use of interspinous process stabilization has recently seen a resurgence of both the number of available devices and their surgical indications.² Interspinous devices currently in clinical use in the United States and Europe include the Wallis device, DIAM, Coflex, Extensure H2, Aperius, and X-Stop. Proposed indications for these devices include treatment of lumbar spinal stenosis in patients with grade 1 degenerative spondylolisthesis, discogenic low back pain, recurrent lumbar disc herniation, and facet syndrome.³⁻⁷ Interspinous devices share a common goal of distraction between adjacent spinous processes, leading to decreased intersegmental motion, decreased foraminal and central stenosis, as well as alterations in load transfer across the motion segments in the lower lumbar spine. In this chapter, we will review the existing scientific literature concerning interspinous process spacer devices with regard to both biomechanical and clinical efficacy.

BIOMECHANICAL AND IMAGING STUDIES

Interspinous devices can broadly be divided into static and dynamic categories. Static spacers have been made

out of titanium, polyetheretherketone, and allograft bone. They are noncompressible and designed to maintain a minimum amount of distraction between the spinous processes of the diseased intervertebral level. The Wallis device utilizes synthetic straps to limit segmental motion in both flexion and extension while the Extensure H2 and X-Stop devices are fixed only to the superior spinous process allowing for flexion but providing a fixed block to extension. Dynamic devices are designed to similarly alter intersegmental motion while allowing for motion preservation. The Coflex device is composed of an axially compressible U-shaped piece of metal, while the DIAM device is composed of an elastomeric material.

Distraction of the interspinous processes is intended to cause local kyphosis at the instrumented intervertebral level. This can decrease invagination of the ligamentum flavum increasing canal diameter and also increase the size of the neural foramen. Richards et al.⁸ showed in a cadaveric model that placement of an X-Stop device significantly increased the canal area by 18% and the foraminal area by 25% by blocking extension at the instrumented level. Other investigators have confirmed these findings in vivo with up to 6-month follow-up by comparing magnetic resonance imaging (MRI) before and after X-Stop implantation.^{9,10} Consistent with the purported mechanism of interspinous spacer devices, the increases in canal and foraminal size were seen in the standing and extended positions, but not in flexed positions.

The Wallis device was initially used in patients undergoing surgery for recurrent disc herniation.² The underlying

rationale of this treatment is that distraction of the posterior elements can unload the disc that may have beneficial effects for both surgically and nonsurgically treated symptomatic disc degeneration. Although animal models have shown that sustained increased intradiscal pressures can induce disc degeneration,¹¹ intradiscal pressures of degenerated discs are usually significantly lower than those of healthy discs because of the inability of an incompetent annulus to maintain a loading environment.¹² Animal models suggest that intervertebral distraction may reverse some of the changes caused by compression-induced degeneration.¹¹ Interspinous spacers appear to be capable of reducing intradiscal pressure; one study demonstrated that implantation of an X-Stop device decreased intradiscal pressure by 43–63% with extension, 40–41% in neutral, and 17–38% in flexion.¹³ These effects are concentrated along the posterior annulus and disc that may be relevant in the setting of painful disc herniation.¹⁴ However, effects on restoration of disc height are minimal.¹⁵

A second potential benefit of altered loading across the intervertebral motion segment is unloading potentially painful and degenerated facet joints. Load across the facet joint is increased in extension and has been shown to be decreased by up to 55% following the implantation of an X-Stop device.^{16,17}

Motion sparing technologies have gained popularity due to concerns regarding the potentially deleterious effects of spinal fusion on adjacent motion segments. Multiple studies demonstrate that implantation of interspinous spacers including the X-Stop, DIAM, and Wallis devices decreases motion (flexion less than extension) at the instrumented level.^{3,14,18–21} However, there do not appear to be any changes in segmental range of motion at the adjacent levels. These studies also demonstrate that there is no alteration to the global alignment of the spine following instrumentation. A second described indication for stabilization using interspinous spacers is to restore stability to a segment that has undergone at least partial facetectomy as part of a surgical decompression. Several cadaveric studies have investigated the ability of interspinous spacer devices to restore segmental stability after increasing levels of resection of the facet joints.^{22–24} They appear to show a restoration of normal or near normal stability with levels of resection up to a unilateral complete facetectomy but not bilateral facetectomy. However, the clinical relevance of these findings is unclear.

CLINICAL RESULTS

The X-Stop device is the most extensively studied of the commercially available interspinous spacers, as this was the first such device to gain FDA approval and has served as the predicate device for this class of devices. X-Stop has been studied in two prospective randomized controlled trials. Zucherman et al. compared 100 patients treated with X-Stop to 91 controls managed nonoperatively.^{25,26} Inclusion criteria for the study were stringent. Patients should (1) be older than 50 years of age, (2) have leg, buttock or groin pain with or without axial back pain that is relieved by sitting, (3) be able to sit for minutes without pain, (4) be able to walk greater than 50 ft, (5) have completed greater than 6 months of nonoperative therapy, and (6) have radiographic evidence of spinal stenosis limited to one or two levels. Results at 1 year were analyzed using the Zurich Claudication Questionnaire (ZCQ) and SF-36. However, only the ZCQ was reported at 2 years. They observed clinically greater improvement at all time points compared to the controls with 60.2% of patients reporting improvement in Symptom Severity domain and 57% improvement in physical function at 2 years. A limited 4-year follow-up of 18 patients from the original surgical cohort demonstrated that 78% had a successful outcome assessed with Oswestry Disability Index (ODI).²⁷ Despite some methodologic limitations, this study does suggest that X-Stop is effective for the treatment of a selected group of patients with spinal stenosis.

Anderson et al. also studied the effect of X-Stop implantation in a prospective randomized controlled trial of 75 patients with spinal stenosis and grade 1 spondylolisthesis.²⁸ The reported clinical improvement of 63% of the surgical group versus 13% of nonsurgical controls using ZCQ and SF-36. Of particular note, the surgical procedure was not associated with progression of the patients' spondylolisthesis. However, a case series of 12 patients by Verhoof et al. reported a high rate (58%) of symptomatic progression of the spondylolisthesis requiring a second operation.²⁹ Other noncomparative studies demonstrate varying degrees of satisfactory outcomes.^{15,30,31}

Data regarding the clinical effectiveness of other interspinous spacers is limited and largely composed of studies that are noncomparative and/or retrospective. The developer of the DIAM implant, Jean Taylor, published a series of 104 patients in whom the device was implanted for a variety of lumbar disorders.³² He reported mixed results for improvement of pain and activities of daily living.

Two reports have investigated the effects of implanting DIAM devices following a lumbar decompression.^{33,34} Although, they report generally good results, they fail to demonstrate that any demonstrated improvement is due to the interspinous device beyond what would be expected from the decompression alone.

A notable indication of the Coflex device is implantation of the device at the superior adjacent segment to an instrumented segment at the time of the index surgery in order to “control” the increased motion at the adjacent level following surgery. Although this “topping-off” construct has been demonstrated to decrease the motion at the superior adjacent level, there were no clinical differences (ODI and VAS pain scores) between this construct and those patients who underwent instrumented spinal fusion alone.^{24,35} Coflex implantation after spinal decompression has also been studied in a prospective controlled study by Richter et al.^{36,37} Similar to the DIAM implant, they showed no difference in any clinical parameter between patients with the implant and those undergoing decompression alone with 2-year clinical follow-up.

Senegas has published his results with 13-year mean follow-up following implantation of the Wallis device following decompression for spinal stenosis or disc herniation.³⁸ Twenty of the 107 devices subsequently failed and required removal and segmental fusion. The remaining patients reported sustained benefit from the procedure based upon ODI, SF-36, and VAS pain scores. However, their claim that the use of the device saved patients from requiring spinal fusion is controversial both with respect to their indications for spinal fusion and the lack of a control group to demonstrate the clinical benefit was not due to decompression alone. The effect of the Wallis device has also been studied with respect to its ability to decrease the incidence of recurrent disc herniation following discectomy.³⁹ The authors found the rate of recurrent disc herniation following device implantation was no lower than the published figure in the literature of approximately 10%.

The Aperius device is another implant which has demonstrated good results in a noncomparative prospective study with 12-month follow-up.^{40–42} However, Postacchini et al.⁴³ prospectively compared a cohort of 36 patients with implantation of the Aperius device for spinal stenosis with similar controls undergoing traditional surgical decompression. At 2-year follow-up, only 31% of patients in the Aperius group with severe spinal stenosis had good outcomes assessed with ZCQ and ODI. Patients with moderate stenosis had better outcomes (60%) but there was a

17% failure rate. Aperius group results were uniformly worse than those for open decompression (80–89% good results).

COMPLICATIONS

Common complications following implantation of interspinous devices include spinous process fracture and device dislocation. Talwar et al. demonstrated that the force necessary to insert an X-Stop device in cadaveric spines ranged from 11 to 150 N.⁴⁴ The force necessary to fracture the spinous process was 95–786 N and was highly correlated with bone mineral density, suggesting that osteoporosis contributes strongly to fracture risk. The risk of fracture may also depend on the rigidity of the implant. The loads transferred from the Coflex device to the spinous process are 11.3% of the static load to failure, suggesting that fracture is less likely when using a more flexible implant.⁴⁵

Clinical failures have been reported for the X-Stop implant. Barbagallo et al. reported failure in 8 of the 69 patients (4 fractures, 4 dislocations, 11%) at 2-year follow-up, while Verhoof et al. reported a very high failure rate (58%) in patients with spondylolisthesis.^{29,46} Senegas had a failure rate of 18% using the Wallis device at a follow-up of 13 years.¹⁴ Aperius device failures have been reported at a rate of 17%.⁴³ There is very little data concerning the failure rates of other devices. The treatment of implant failure generally requires removal of the implant and decompression of the affected level.

COST-EFFECTIVENESS

The cost-effectiveness of interspinous devices has been compared to open decompression and conservative management in two studies with differing results. Skidmore et al.⁴⁷ utilized 2-year follow-up data from the X-Stop FDA trial to calculate cost-effectiveness data. They showed that the cost per quality adjusted life-years (QALY) of X-Stop versus conservative management for spinal stenosis was \$17,894. In comparison to open decompression, the X-Stop procedure was dominant in that it was both less expensive and provided better quality of life. This value falls well inside commonly accepted values of cost-effectiveness.⁴⁸ In contrast, Burnett et al.⁴⁹ also performed the same comparisons utilizing pooled data from a variety of sources. They concluded that the open decompression was the dominant treatment with a cost per QALY relative to conservative care of nearly \$60,000. As with all such studies, the conclusions are only as valid as the underlying data and assumptions. Skidmore et al. have criticized the study

by Burnett et al. citing: “(1) inclusion of papers from disparate patient populations, (2) use of untransformed SF-36 scores rather than utilities to inform QALYs, (3) inconsistent definitions of treatment failure, (4) lack of consideration about the frequency and costs associated with spinal fusion, and (5) outdated X-STOP payment mechanisms and amounts.” Clearly, further work is necessary to clarify this issue.

CONCLUSION

There are a wide variety of interspinous implants currently available for use in the United States and Europe. All share a common goal of interspinous process distraction leading to increased area of the spinal canal and neural foramen. Altered loading across the intervertebral motion segment may be beneficial, but these indications have not been clinically proven. The X-Stop device is the best studied with Level 1 evidence demonstrating its efficacy in the treatment of spinal stenosis and spinal stenosis with grade 1 spondylolisthesis.^{25,28} Data regarding the other devices is limited, but further clinical trials are underway. In the rare instances when interspinous devices have been compared directly to surgical decompression, the clinical results favor surgical decompression especially for patients with

severe spinal stenosis, but the cost-effectiveness data does not clearly favor one intervention over the other. We agree with the assessment of Sobottke et al. that patients suitable for implantation of interspinous process devices are relatively uncommon.⁵⁰ Only 17.5% of >1,000 patients in their series with intermittent neurogenic claudication met the criteria for implantation.

In our practice, we feel that interspinous process devices are beneficial for a very narrow group of carefully selected patients. Our indications include a clear story of intermittent neurogenic claudication with complete resolution of symptoms in the seated/flexed positions and evidence of mild-to-moderate spinal stenosis on MRI limited to one or two levels. We are more inclined to recommend an interspinous process device in those patients with disabling symptoms and concomitant multilevel pathology such as degenerative scoliosis or spondylolisthesis where a formal decompressive laminectomy might further destabilize the spine and require a spinal fusion (Figs. 81.1A and B). Some authors have also advocated the use of interspinous process devices in conjunction with discectomy for treatment of symptomatic disc herniation citing improvements in low back pain but this is not something we have incorporated into our practice.^{51,52}



Fig. 81.1A: A 67-year-old man with bilateral neurogenic claudication symptoms only with standing/walking. Preoperative anteroposterior radiographs demonstrate a degenerative scoliosis. Representative T2-weighted sagittal and axial magnetic resonance imaging demonstrate a segment with moderate stenosis.



Fig. 81.1B: Two-year follow-up radiographs after implantation of an X-Stop device at L3/4 and L4/5 demonstrate a stable degenerative scoliosis without development of any new instability. The patient continues to have an excellent symptomatic result.

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Operative Treatment of Low-grade Lumbar Degenerative Spondylolisthesis

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Snapshot

- » Etiology and Demographics
- » Classification Systems
- » Clinical Presentation/Characteristics
- » Operative Indications
- » Operative Approaches
- » Costs
- » Complications

INTRODUCTION

Degenerative spondylolisthesis (DS) is the translational displacement of one vertebral segment over an adjacent, inferior level as a consequence of degenerative changes, including aging and arthritis, that affect the integrity of the intervertebral disc and facet joints (Fig. 82.1).^{1,2} Degenerative spondylolisthesis was initially referred to as pseudo-spondylolisthesis by Junghanns due to the presence of an intact neural arch.^{2,3} The intact neural arch distinguishes DS from what, at the time, was thought to characterize spondylolisthesis: the presence of a defect in par inter-articularis or the isthmic region of the vertebral segment.² However, because all forms of spondylolisthesis involve a forward slippage of the cephalad vertebra in a spinal segment, Macnab referred to this condition as “spondylolisthesis with an intact neural arch.” Later, Newman coined the term “degenerative spondylolisthesis.”^{4,5} Unlike isthmic spondylolisthesis, DS is typically seen in middle-aged or older individuals and may be associated with symptoms from the presence of stenosis of the spinal canal and/or neural foramen.

ETIOLOGY AND DEMOGRAPHICS

Various factors have been suggested to play a role in the development of DS. Normal facet joints in the lum-



Fig. 82.1: Lateral X-ray of L4/L5 degenerative spondylolisthesis.

bar spine carry up to 33% of the axial load and between 3% and 35% of the compressive load, depending on the specific level and patient posture. As degeneration of the intervertebral disc ensues, the compressive loads on the facet joints can increase substantially, leading to facet joint degeneration and remodeling.⁶ Coronally oriented facet joints provide superior resistance to shear forces.⁷ The orientation of the facet joints can vary between individuals and between vertebral levels. In addition, with facet degeneration, it has been suggested that more

sagittally oriented facet joints may be produced.⁸ In addition, Blumenthal et al found that patients who had a facet angle of greater than 50° let to a 39% chance of slip progression in the setting of degenerative spondylolisthesis after a decompression alone.⁷⁰

A role for ligamentous laxity in DS has also been suggested. Most cases of DS occur at the L4–L5 or L3–L4 segments. The condition rarely affects the L5–S1 segment where ligamentous support is more robust despite the substantial shear forces present at the lumbosacral junction.⁹ Females are affected by DS much more commonly than males, which may be attributable in part to increased ligamentous laxity. Rosenberg et al. found DS to be four times more common in women and seldom observed the condition prior to the age of 50 years.⁹ Women not only develop DS more frequently than males, but also at a younger age.¹⁰ Imada et al. suggested a role for estrogen in the development of DS, demonstrating that oophorectomy was a positive risk factor for DS, despite similar facet orientation.¹⁰ Nadaud et al. did not find estrogen receptors in facet joint capsular ligaments in 14 samples of DS patients; therefore, the effect of estrogen may be indirect.¹¹

CLASSIFICATION SYSTEMS

Meyerding classified spondylolisthesis according to the degree of slippage: 0–25%, grade 1; 26–50%, grade 2; 51–75%, grade 3 and 76–100%, grade 4 (Fig. 82.2). Slippages greater than 100% are called either grade 5 or spondyloptosis.¹ The percentage of slip according to Meyerding is calculated as a/A , where a is the numerical measurement of how far the segment is displaced in an anterior direction, and A is the anteroposterior diameter of the segment on which the slippage has occurred.¹ Low-grade slips include grades 1 and 2. Pure DS almost exclusively involves low-grade slippage—most often grade 1 or 2.^{1,9}

Among cases of lumbar DS, there is significant heterogeneity in the radiographic characteristics of the slippage.¹² Surprisingly, no well-accepted classification system has yet been described for lumbar DS. Anderson et al. studied the radiographic characteristics of DS at the L4–L5 level to identify useful parameters in developing a clinically relevant classification system.¹² The data for angular and translational movement on neutral, flexion, and extension films were generally continuous in nature, suggesting a wide spectrum in the range of instability with this condition.¹²



Fig. 82.2: Meyerding classification system: lateral radiograph of a lumbar spine with spondylolisthesis at L4/L5 level.

Adding some radiographic parameters which is associated with DS, such as pelvic incidence, global alignment.

CLINICAL PRESENTATION/CHARACTERISTICS

Symptoms in DS patients can vary widely from asymptomatic, to back pain predominant symptoms, to those with severe symptoms of radiculopathy or neurogenic claudication. Collapsed disc space, ossified ligaments, sclerosis of cartilaginous endplate, and vertebral body spur formation are negative predictors for slip progression¹³; however, there is no specific correlation between the degree of slippage, slip progression and the onset or severity of symptoms in DS.^{13–17}

The symptoms most commonly requiring surgical management are those associated with spinal stenosis, including neurogenic claudication and radiculopathy caused by compression of neural elements at the site of the slippage.^{14,18–22} Leg pain symptoms in a unilateral or bilateral distribution are generally worse with standing and/or ambulation and better with forward flexion of the spine (e.g. with sitting or leaning on a shopping cart).¹⁸ Because symptom severity is not directly correlated with the degree of spinal canal narrowing, patient history plays the predominant role in clinical decision-making regarding the need for treatment in DS.²³

Radiculopathy from DS most commonly affects the L4–L5 segment and causes L5 radiculopathy, although symptoms of L4 nerve root compression may occur, if

significant stenosis exists in the L4–L5 foramen.^{19,24} Leg pain symptoms may follow either a classic dermatomal distribution or involve crampy pain in the buttock, thigh, and/or calf that progresses in a proximal to distal manner with standing and walking.²⁴

Nonoperative options for affected patients include activity modifications, nonsteroidal anti-inflammatory drugs, epidural injections, analgesic or nerve membrane stabilizer medications and exercise-based rehabilitation programs. Patients with severe or progressive symptoms despite nonsurgical care are generally considered candidates for surgery.

■ OPERATIVE INDICATIONS

Decision-making with DS, on the part of the clinician, is complex and involves careful consideration of the patient's symptoms, disability caused by the disease, response to treatment and medical history. Unfortunately, nonoperative treatments usually do not produce long-term relief for those with severe, long-standing or recurrent leg pain in the setting of DS.^{14,22,25,26} The Spine Patient Outcomes Research Trial (SPORT) was a study designed to follow both a randomized and an observational cohort with DS subsequent to operative or nonoperative treatment for DS. Weinstein et al. reported that operative treatment resulted in superior patient outcomes in terms of decreased pain and functional recovery using patient-based outcome measures.²⁷

■ OPERATIVE APPROACHES

Simple Decompression

Surgical decompression addresses the issue of stenosis-induced symptoms for patients with DS, but it does not address the potential instability of the spinal segment.²⁸ Traditionally, decompression has involved a lumbar laminectomy. Some have suggested that a wide laminectomy is necessary to reduce the risk of bone regrowth and resulting recurrent stenosis.²⁹ Unfortunately, wide lumbar decompression is associated with a risk of progressive spinal instability that can lead to a recurrence of symptoms and poor clinical outcome.²⁹

Several authors have reported that simple decompression can be an effective means of treating DS.^{14,30} Dall and Rowe suggested that patients subjectively improve more with laminectomies and partial facetectomies compared to laminotomies or foraminotomies, and thus advocated a

more extensive decompression.¹⁶

Several studies have found that patients are prone to postoperative slip progression following wide laminectomy.^{14,15} This may be due to the loss of stability associated with the removal of posterior ligamentous structures (supraspinous, interspinous ligaments, and ligamentum flavum) and the resection of portions of the facet joint as part of the decompression.³¹ Some have reported that more extensive decompressions, involving a greater number of levels, present a higher risk for postoperative instability.^{20,32} However, in Rosenberg's experience, postoperative slippage often ceases following the first year.²⁰ Unfortunately, instability of the segment may be a source of additional symptoms, requiring revision surgery.¹⁴ For this reason, patients should be informed regarding the possible need for additional surgical intervention if a decompression alone is done in the setting of DS.³⁰

Proponents of decompression alone for DS argue that the increase in the cost of doing a fusion may not be warranted in all cases.^{33,34} Kim et al. suggested that patients with stable spondylolisthesis and leg-dominant pain could be adequately treated by simple decompression, without fusion, based on the substantial increased costs of a fusion with only minor gains in clinical outcome.³³

With the advent of less invasive or minimally invasive decompression techniques, there has been the resurgence in interest for decompression alone as a treatment strategy for DS with leg-dominant symptoms.³⁴ Kelleher et al. demonstrated that decompression alone using a minimally invasive technique could produce favorable clinical results with substantially less morbidity compared to lumbar fusion.³⁴

Decompression and Uninstrumented Fusion

The use of fusion to supplement decompression in the setting of DS has been debated.³⁵ Unfortunately, it is not always easy to compare various clinical series in the literature due to differences in patient demographics, surgical technique and methods of measuring clinical outcome.^{35,36}

Martin et al., in a retrospective cohort study, demonstrated a decreased likelihood of reoperation following a decompression and fusion compared to simple decompression alone.³⁷ Herkowitz and Kurz published a landmark prospective, randomized study involving 50 patients with DS treated by either simple decompression or decompression with an uninstrumented fusion.³⁵ In this study,

they found that posterolateral fusion yielded superior outcomes compared to decompression alone. Surprisingly, the clinical outcomes in the fusion group were more favorable irrespective of whether patients achieved a successful radiographic fusion.³⁵ The use of fusion combined with decompression has been routine in the practice of many surgeons when treating DS, based in large part on Herkowitz and Kurz's study.³⁵ In the SPORT study, 95% of surgical subjects enrolled underwent fusion, despite the absence of a requirement to use fusion for this diagnosis in the study protocol.²⁷

Postacchini and Cinotti studied the long-term outcomes of patients treated surgically for spinal stenosis.²⁹ They found some degree of bone regrowth in all patients regardless of whether or not a fusion had been performed. The magnitude of bone regrowth was significantly less, however, in those treated with a fusion.²⁹ Patients with more bone regrowth had worse clinical results, compared to those with less bone regrowth.

While decompression and fusion, without instrumentation, is more costly compared to decompression alone, it is still substantially less costly compared to an instrumented fusion.³⁸

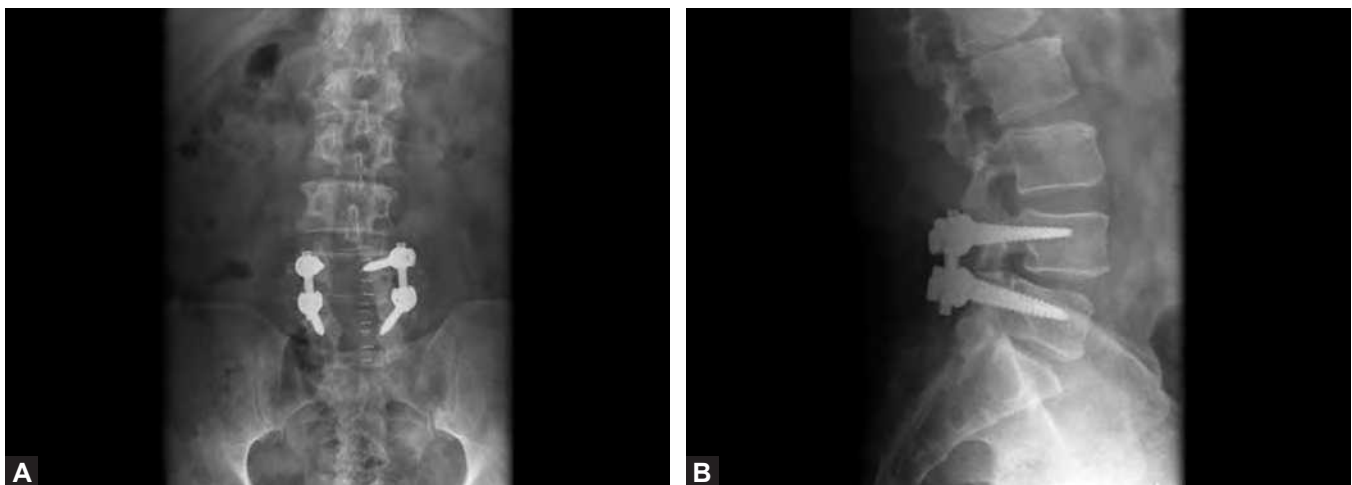
Decompression and Instrumented Fusion

The use of spinal instrumentation, usually involving pedicle screw fixation (Figs. 82.3A and B), to supplement spinal fusion has also been debated.³⁸ Despite this, supplemental instrumentation for those patients with DS undergoing

decompression and fusion has become commonplace in the United States due to the touted advantage of an increased fusion rate.^{33,34,39} Unfortunately, improvement in long-term clinical outcome with the use of spinal instrumentation has yet to be proven conclusively. One reason for the difficulty in interpreting the clinical data available in the literature on this topic is an overreliance on radiographic results instead of a focus on patient-based clinical outcomes.²⁵ Only in recent years have patient-based outcome measure begun to become commonplace in clinical studies.

Fischgrund et al. performed a prospective, randomized study comparing the effects of decompressive laminectomy and fusion with and without supplemental instrumentation.³⁹ They found a significantly higher fusion rate when pedicle screw fixation was used (82% compared to 45% without). Despite this, no significant improvement in clinical outcome was found for the patient cohort treated with pedicle screw instrumentation. In this study, radiographic fusion did not correlate strongly with clinical outcome and patients with a "fibrous union" achieved a favorable clinical outcome in some instances. In a longer-term follow-up study of the same patient population, Kornblum et al. found less back and lower leg pain in patients who had achieved successful arthrodesis (86% vs. 56% good/excellent), suggesting a potential clinical benefit for spinal instrumentation at least in the long run.²⁶

Bridwell et al. performed a prospective, randomized study of 49 patients with an average follow-up of 3 years.⁴⁰ In this study, they included three treatment groups: Group 1, no fusion; Group 2, decompression and fusion; and



Figs. 82.3A and B: Anteroposterior and lateral radiograph following posterolateral fusion and pedicle screw fixation.

Table 82.1: Comparison of the pros and cons of simple decompression, decompression with fusion, and decompression with instrumented fusion.

	<i>Pros</i>	<i>Cons</i>
Decompression	<ul style="list-style-type: none"> • Addresses the issue of stenosis • Cost-effective compared to fusions • May be the optimal choice for certain types of degenerative spondylolisthesis 	<ul style="list-style-type: none"> • Does not address the issue of instability • Risk of bone regrowth • Postoperative slip progression • Instability may require revision surgery
Decompression and uninstrumented fusion	<ul style="list-style-type: none"> • Addresses issue of stenosis and instability • Superior clinical outcomes to simple decompression whether fusion is achieved or not • Lower amount of bone regrowth post-decompression 	<ul style="list-style-type: none"> • Higher costs compared to simple decompression • Decreased fusion rate when compared to instrumented fusion
Decompression and instrumented fusion	<ul style="list-style-type: none"> • Benefits of uninstrumented fusion with the added benefit of higher fusion rates • May be superior to uninstrumented fusion because of some evidence associating pseudoarthrosis with decreased clinical outcomes 	<ul style="list-style-type: none"> • Significantly more expensive when compared to simple decompression or decompression and uninstrumented fusion • Short-term clinical benefits are not superior to those of uninstrumented fusion

Group 3, decompression and fusion with pedicle screw fixation.²⁶ As with the Fischgrund study, Bridwell et al. found a significant increase in fusion rate with instrumentation (87% compared to 30%). Walking capacity, the only functional measure collected in the study, improved more in the patients who achieved a successful fusion. In addition, less slip progression was noted in the instrumented group compared to the other groups.

Yuan et al. performed a large, historical cohort study with 2,684 subjects with DS.⁴¹ They found that patients with pedicle screw fixation achieved a higher fusion rate compared to those who underwent uninstrumented fusion. The fused patients also enjoyed better functional outcomes and superior regression of neurological symptoms.⁴¹ Despite the risk of implant breakage and loosening, the authors concluded that the use of pedicle screw fixation outweighed the drawbacks.⁴¹

In contrast, Thomsen et al. studied the use of pedicle screws for lumbar fusion and found that the complications associated with pedicle screw fixation were high, potentially outweighing the benefits.⁴² In their prospective, randomized trial involving 130 subjects, patients were randomized to fusions with or without pedicle screw instrumentation. The authors reported increased blood loss, operative time, risk of nerve injury, and revision rates in the group receiving instrumentation.⁴² It should be noted, however, that this older study may not be representative of current complication rates, as most technical complications have been shown to be reduced with increased surgeon experience.⁴³⁻⁴⁵

Ultimately, each of the aforementioned surgical approaches is coupled to pros and cons that a surgeon must take into consideration on a case-to-case basis when treating DS (Table. 82.1). Because of this, an open discussion of the options, risks and benefits for the treatment of DS should be conducted with the patient, leading to the opportunity for shared decision-making.

Forsth et al. recently published a randomized control trial of fusion vs decompression for lumbar stenosis in 247 patients (Swedish Spinal Stenosis Study). Of those patients, 135 patients had both stable and unstable degenerative spondylolisthesis. Degenerative spondylolisthesis in that study was defined as greater than a 3 mm slip without flexion extension views taken; the average preoperative slip was 7.4 mm. Two and five year follow up found that there were no differences in visual analogue pain scores, Oswestry Disability Index, and all other patient reported outcome measures between the two groups. However, it should be noted that 20% of the decompression patients had it performed minimally invasively. The re operation rate at 6.5 years was 22% in the fusion group and 21% in the decompression group.⁷¹ Ghogawala et al. published a randomized control trial in North America of 66 patients of fusion vs decompression for degenerative spondylolisthesis (SLIP-Spinal laminectomy vs Instrumented pedicle screw trial). All of the patients had a Grade 1 stable spondylolisthesis and excluded patients who had a >3 mm translation on flexion extension views. The average preoperative slip was 6 mm with 1.5 mm of translation. At 1, 2, and 4-year follow-up, fusion was better than decompression for the PCS (physical component score of the SF-36) at all time

points though there were no differences in the Oswestry Disability Index. The reoperation rate was 34% in the decompression group vs 14% in the fusion group.⁷² The conclusions of both studies do not clearly differentiate between “stable” vs “unstable” slips. There are obvious differences between patients who have a collapsed disc with fixed slips vs those with a large disc, bulky fluid filled facets, and >4 mm of dynamic instability. Despite slip progression, a “stable” degenerative spondylolisthesis may be adequately treated with a decompression alone. However, the ideal treatment of an “unstable” degenerative spondylolisthesis remains unknown. Revision surgery was at the discretion of the surgeon which may skew rates of revision surgery in both the Forsth and Ghogawala study.

Interbody Fusion

The rationale for interbody fusion involves the potential benefits associated with increasing anterior column support, increasing the area for fusion and re-establishing interbody height.⁴⁶ The drawback of interbody fusion involves the increased surgical complexity and cost of an interbody fusion procedure. The risks and benefits must be weighed in light of the patient’s particular situation when deciding on a surgical approach.

Posterior Lumbar and Transforaminal Lumbar Interbody Fusion

Using either a posterior lumbar interbody fusion (PLIF) or transforaminal lumbar interbody fusion (TLIF) approach, surgeons are able to reconstruct the disc space during the surgical procedure for DS.^{47,48} It is important for the surgeon to be experienced with the specific technique chosen as the risks and complexity of an interbody fusion are generally greater compared to posterolateral fusion.^{46,49} Although surgeon preference plays a role in surgical decision-making, the cost, operative time and patient morbidity must be considered as a part of the decision.

The more popular approach currently is the TLIF, which was described by Harms and Jerszenszky as a modification to the PLIF procedure.^{46,48} Transforaminal lumbar interbody fusion is felt by many to be the simpler and safer operation due to the reduced need for dural retraction and the simplified reconstruction of the disc space. When comparing TLIF and PLIF, Humphreys et al. showed that PLIF patients had greater blood loss, length of hospital stay, and operative time, while the TLIF patients sustained fewer

complications.⁵⁰ However, modern PLIF surgeons have generally modified the older PLIF approach to include wide removal of the facet joints, making the modern PLIF approach safer compared to the older PLIF technique and more similar to a bilateral TLIF.

Patients with DS may, in some cases, present challenges with a PLIF or TLIF procedure. Patients with significant stenosis will require substantial removal of the facet to provide safe access to the lateral disc space. In addition, patients with severe disc space collapse may have minimal room caudal to the exiting nerve root, thus limiting access to the disc space. Also, older patients with significant osteoporosis may not have adequate bone quality in the endplate region to support interbody devices and can have a high rate of inadvertent endplate violation during disc space preparation. Despite these challenges, PLIF and TLIF are useful adjuvants to the surgical care of selected patients with DS.

Anterior Lumbar Interbody Fusion

Anterior lumbar interbody fusion (ALIF) provides excellent access for disc space preparation and grafting. However, this approach presents the risk of injury to major vital structures and may require the assistance of an exposure surgeon. In addition, the ALIF procedure fails to provide access to decompress the subarticular region where there is often facet hypertrophy causing neural compression. Thus, ALIF may need to be combined with posterior column decompression and fusion to provide both stabilization and subarticular decompression. For these reasons, ALIF is less commonly performed compared to posterior-only approaches for DS. Despite this, there are patients where ALIF may be a reasonable consideration. Satomi et al. recommended the use of ALIF for early stage DS when the nerve compression symptoms were related more to instability as opposed to structural facet hypertrophy.⁵¹ Another situation where ALIF may be considered is when stenosis predominantly affects the foraminal zone with less significant lateral recess or central narrowing. Interbody distraction is capable of achieving “indirect” decompression of the foraminal zone in many such cases, without the need for a laminectomy. Inoue et al. also found ALIF to be a reliable solution for selected cases of DS, particularly those with significant segmental instability who were younger than 60 years of age.⁵² The later stages of DS have generally been found to require additional

decompression of the posterior column to achieve adequate decompression.⁵¹

Minimally Invasive Procedures

Minimally invasive procedures are attractive from the standpoint that they potentially offer a way to reduce perioperative morbidity, recovery time, and pain.⁵³ Unfortunately, strong evidence favoring minimally invasive surgery over traditional surgery for DS is currently lacking in the literature.⁵³ In addition, the steep learning curve associated with minimally invasive approaches prevents many surgeons from considering this option.⁵³

Rampersaud et al., in an observational cohort study, demonstrated a significant decrease in the length of hospitalization and blood loss along with a decreased need for a blood transfusion for patients treated with a minimally invasive surgical approach.⁵³ They also found reduced costs with minimally invasive surgery, due in large part to reduced hospitalization.⁵³

Wang et al. studied 85 patients following either traditional, open TLIF or a minimally invasive TLIF.⁴⁸ In this study, the operative times and postoperative radiographic results were similar for both groups; however, the minimally invasive group demonstrated a significantly shorter hospital stay, less blood loss, less need for transfusion and decreased back pain.⁴⁸ One drawback of the minimally invasive approach was the substantial increase in the use of fluoroscopy.⁴⁸ Price et al found that minimally in-

vasive TLIF produces comparable clinical and radiologic outcomes (90% fusion rates in both groups) to open TLIF with the benefits of decreased intraoperative blood losses, shorter operative times, shorter hospital stays, and fewer deep wound infections.⁷³

Lateral interbody fusion (XLIF or DLIF) is another less-invasive fusion technique that has gained popularity in recent years (Fig. 82.4). This approach provides access to the lumbar spine above the L5-S1 level utilizing the retroperitoneal space and transpsoas approach.⁵⁴ This approach has been recently assessed by Marchi et al. who suggested that the lateral approach was beneficial in patients with low-grade DS.⁵⁵ Although the approach has certain advantages including reduced soft tissue morbidity, preservation of the anterior and posterior longitudinal ligaments, and good interbody distraction, there are also drawbacks to consider including increased cost, the possible need for additional posterior column surgery and the risk to adjacent structures in the region of the operative field. As with other interbody approaches, the XLIF/DLIF approach may be useful in selected cases of DS. Patients who are candidates for lateral fusion without direct decompression have stenosis secondary to dynamic compression (i.e. patients who have pain with walking/standing that reduces with sitting or laying flat in the setting of >4 mm of instability of 10° kyphosis). Radiographic analysis should show reduction of the spondylolisthesis on a supine (CT, X-ray, or MRI) when compared to an extreme flexion X-ray. Candidates who have lateral

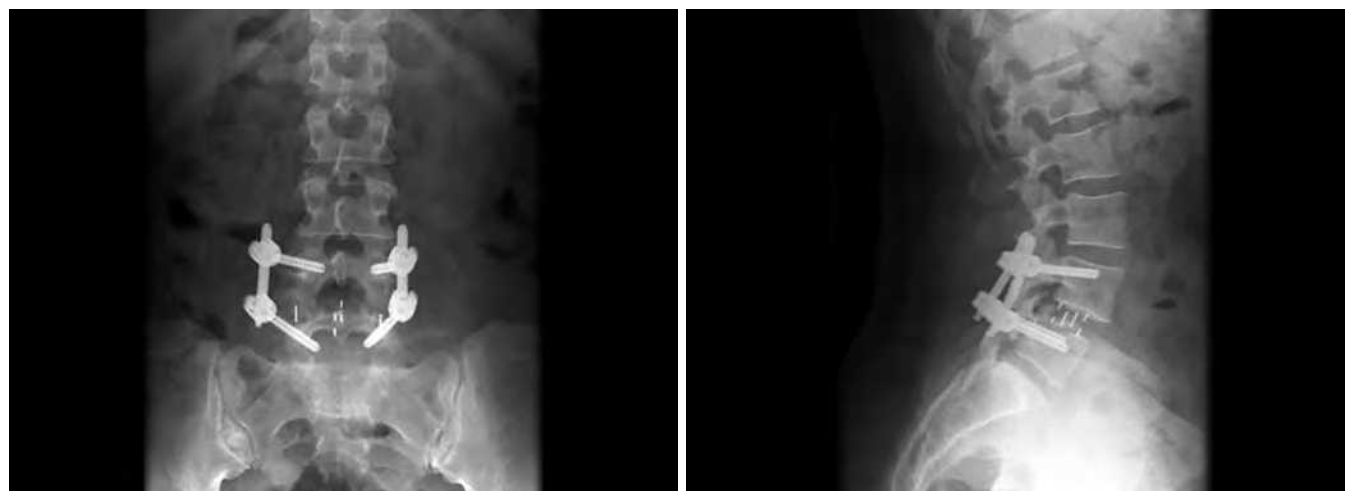


Fig. 82.4: Anteroposterior and lateral X-ray following direct lateral interbody fusion and percutaneous pedicle screw fixation.

recess and foraminal stenosis are better candidates for indirect decompression than those with central stenosis.

Nonfusion Strategies

Presently, decompression with fusion is the most common surgical approach used for lumbar degenerative instabilities.⁵⁶ However, concern over the effects of fusion on adjacent vertebral segments has led some to consider alternatives to lumbar fusion for the DS population. A variety of medical devices have been studied in small patient cohorts to provide stabilization without arthrodesis. Unfortunately, most of these devices have not yet been subjected to rigorous clinical studies and therefore strong evidence for the efficacy of these devices is currently lacking in the DS population.⁵⁷ Broadly speaking, the devices can be divided

into interspinous devices, pedicle-based devices and facet replacement devices.

Examples of the interspinous devices would include the X-STOP (Fig. 82.5) and Coflex (Fig. 82.6).⁵⁶⁻⁵⁸ Different interspinous devices restrict spinal motion in various directions depending on the design of the specific device. Some studies have suggested that interspinous devices were capable of achieving superior clinical results compared to nonoperative treatment or even fusion.^{57,59,60} The overall complication rate with initial implantation of interspinous devices has generally been low.^{59,60} Unfortunately, symptomatic relief may not last and revision surgery may be required in a substantial proportion of patients with instability and stenosis treated with an interspinous device.⁶¹

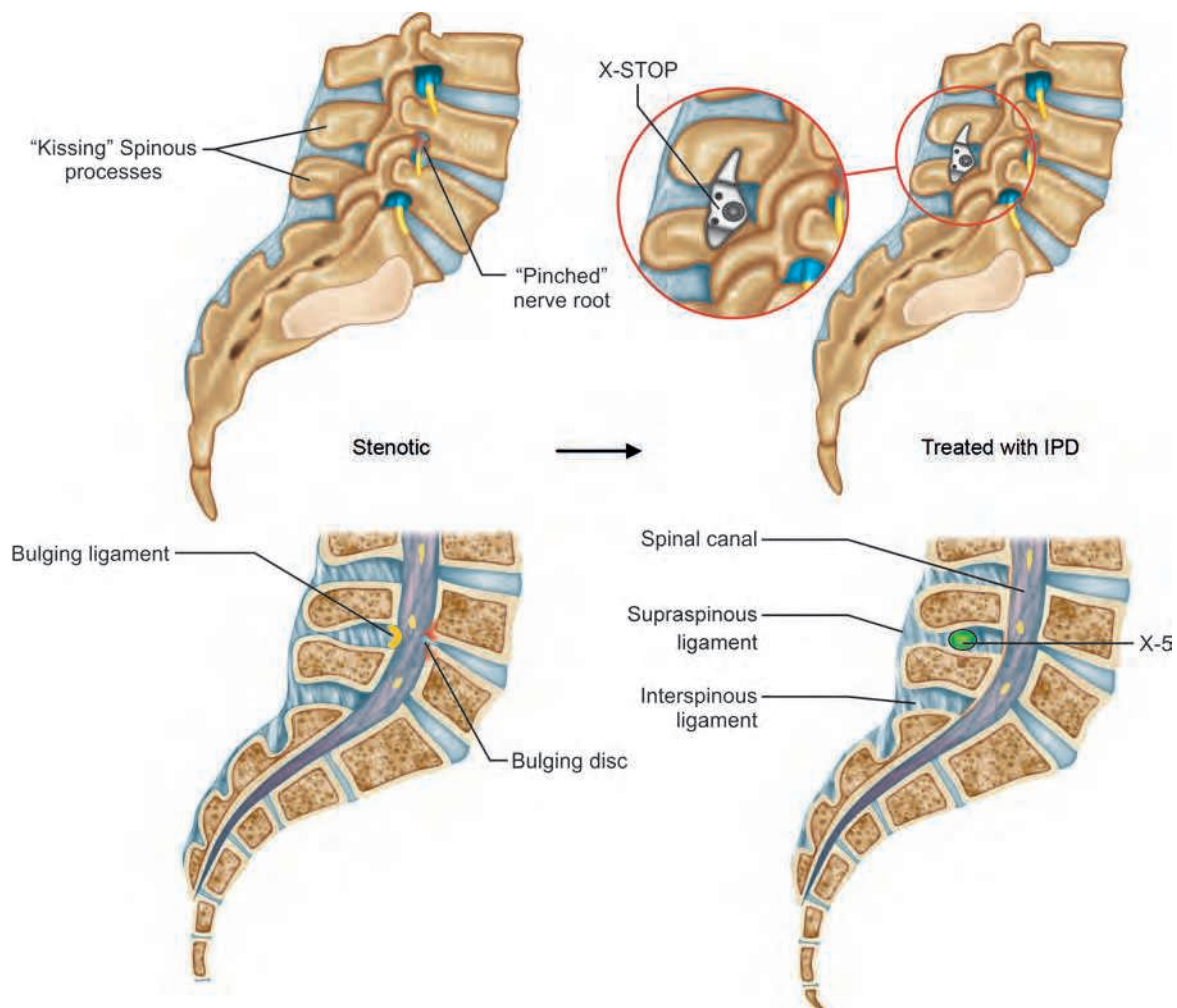


Fig. 82.5: Lateral and posterior view of implanted X-STOP device.

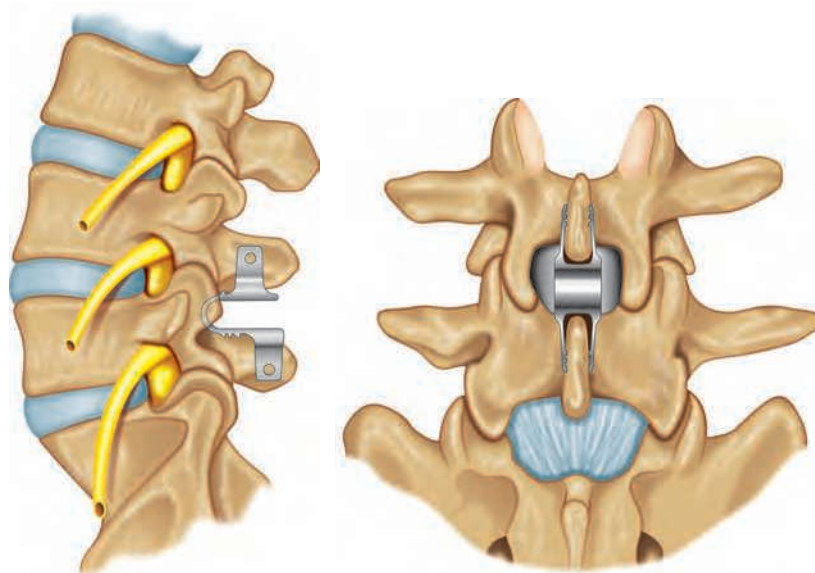


Fig. 82.6: Lateral and sagittal views of implanted Coflex device.

COSTS

Costs associated with spinal interventions have fallen under increased scrutiny in recent years. Between 1997 and 2005, the aggregate total costs of spine care rose by 65%.⁶² However, during this time, patient care and outcomes failed to demonstrate a corresponding increase.⁶⁷ Economic realities have led to the push for a value-based healthcare system. Such a system would take into consideration the cost-effectiveness of an intervention based on its estimated value—defined as quality over total costs. Attempts to measure the parameters of quality and costs have unfortunately been complicated and slowed the movement toward such a value-based system. Currently, there is debate over which factors appropriately qualify for the measurement of quality and costs. Although there is no lack of costs analyses for spine care in the literature, the available studies generally have limitations and the field of cost analysis requires additional standardization in methodology before it will be possible to smoothly compare the value of various approaches to spinal problems.

Most often, the cost-effectiveness of an intervention is measured as costs per quality adjusted life year (QALY). In the United States, the traditional threshold for a cost-effective intervention is one that costs less than \$100,000 per QALY.⁶³ Using the 2004 Medicare payment rate, Tosteson et al. calculated the costs per QALY for the surgical treatment of DS over nonoperative care at \$115,600 although this cost would be expected to reduce if the treatment effect gained through surgery showed longer durability.⁶¹

Longer-term studies will be required to define better the true cost-effectiveness of surgery for DS.⁶⁴

COMPLICATIONS

Potential complications are inherent to all surgical interventions. However, with knowledge, experience and meticulous technique, complications can be minimized.⁴⁹

In addition to the general surgical complications, treatment of DS by lumbar decompression without fusion risks complications such as iatrogenic facet, pars fracture or future instability. In addition, there is a risk of bony regrowth and restenosis, requiring additional surgery.^{14,15,29} As with all decompressions, postoperative hematoma can lead to neurologic deficits.⁶⁵

With larger and more complex surgeries, the risk of complications increases. Deyo et al. found that subjects undergoing fusion, compared to those with simple decompressions, had a 5.8 times greater rate of blood transfusion, a 2.2 times greater nursing home placement rate, a 1.5 times higher rate in hospital charges, and a 1.9 times greater complication rate.⁶⁶ Pseudarthrosis and instrumentation failure are potential complications of fusion procedures.^{26,41} Smoking and diabetes have been shown to decrease the rate of successful fusion.⁶⁷ Following fusion, motion of adjacent levels may be increased and this theoretically may lead to the risk of adjacent segment degeneration, requiring additional surgery.⁵⁷ The risk for this may be higher in postmenopausal women.^{57,68} Neurologic complications, while rare, may occur with any spinal

procedure. Hosono et al. found that prolonged operative time was a risk factor for neurological complications, due to prolonged retraction of the dura or nerve roots.⁶⁹

KEY POINTS

- Degenerative spondylolisthesis is the translational displacement of a vertebral segment over an adjacent, inferior level as a consequence of degenerative changes including aging and arthritis that affect the integrity of the intervertebral disc and facet joints.
- Patients with DS can vary widely from asymptomatic, to those with back pain predominant symptoms, to those with severe symptoms of radiculopathy or neurogenic claudication from spinal stenosis.
- For most patients, nonoperative or conservative treatments provide at least some temporary symptom relief; however, in patients with severe symptoms who fail to respond to nonsurgical care, operative intervention is generally more successful in reducing symptoms.
- Currently, the most common surgical approach for patients with DS involves performing a decompression and fusion procedure.
- The benefits of supplemental pedicle screw instrumentation continue to be debated, although instrumentation has been associated with a higher rate of radiographic fusion success.
- Recently, there has been interest in the spinal community regarding the use of minimally invasive and nonfusion devices for the DS population. The current literature is still inconclusive on the role of these developing treatment strategies.

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Operative Treatment of High-grade Lumbar Spondylolisthesis

Eiji Okada, Morio Matsumoto

Snapshot

- » Clinical Symptoms
- » Treatment
- » Fusion with Reduction
- » Surgical Techniques
- » Case Presentation

INTRODUCTION

High-grade lumbar spondylolisthesis, which is of grade 3 or more by the Meyerding classification, or has a percent slip of 50 or more, is rare compared to the low-grade spondylolisthesis.^{1,2} There are two types of high-grade lumbar spondylolisthesis: (1) the L5 simply slips anteriorly with respect to S1 (low-grade dysplastic type by the Marchetti classification)³ and (2) the L5 vertebral body slips anteriorly and rotates around S1's superior end plate, i.e. the defect involves both the vertebral slip and kyphosis at the lumbosacral junction as a result of vertical sacral slope (high-grade dysplastic type).³ Posterior reduction is typically indicated for the low-grade dysplastic type, whereas the high-grade dysplastic type often requires lumbosacral kyphosis correction in addition to slip reduction.

Spondylolisthesis occurs and progresses most frequently during the growth period. In contrast, slip progression is rare after skeletal maturity. Biomechanical studies suggest that the slip occurs between the growth plate and the osseous end plate, which is biomechanically weak.^{4,5} The pathomechanism of the rounding deformity of the sacrum involves deficient endochondral ossification of the growth plate in the superoanterior corner of the S1 vertebra.^{6,7}

CLINICAL SYMPTOMS

According to Boxall et al.,⁸ only a few patients (4.7%) with high-grade spondylolisthesis are asymptomatic. Low back

or buttock pain is the most frequent complaint (79%). The exact mechanism of low back pain is still unclear. However, segmental instability or pars defect is likely to impact the onset of clinical symptoms. Heart-shaped or flattened buttocks are often seen in patients with high-grade spondylolisthesis. Tight hamstrings (65%)⁸ may contribute to sagittal imbalance and difficulty walking. The typical gait pattern is described as a "pelvic waddle" in which patients walk with their knees slightly flexed. The hyperlordotic lumbar spine and hips are stiff, and there is a tendency to walk on toes⁹ (Fig. 83.1). Uni- or bilateral radiculopathy to the thigh, leg, or foot is also frequently seen (62%).⁸ The step-off or displacement of spinous processes may be noted. During preoperative evaluation, patients should be carefully examined for motor and sensory deficits of the lower extremities. Rare bladder dysfunction can also occur in patients with high-grade spondylolisthesis.¹⁰⁻¹² Therefore, bowel and bladder function should be carefully assessed as well.

Regional and global spine alignment and flexibility should be checked before surgery.

TREATMENT

The natural history of high-grade spondylolisthesis has received little attention in the literature. Although low-grade spondylolisthesis has been shown to cause symptomatic

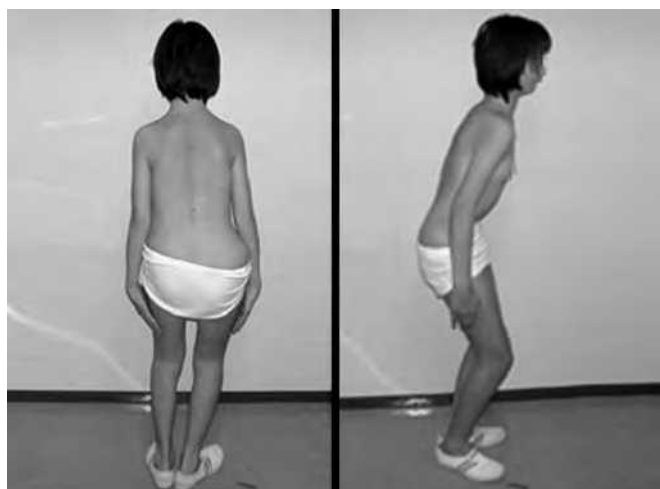


Fig. 83.1: Standing posture of a patient with high-grade spondylolisthesis.

progression in only a small percentage of subjects in long-term follow-up studies,^{2,13} the majority of high-grade spondylolisthesis patients develop significant symptoms at an early age. Therefore, many surgeons recommend surgery for high-grade spondylolisthesis.¹⁴⁻¹⁶ After skeletal maturity, significant progression of the slippage can occur, accompanied by worsening symptoms and limitations in activity, even though the patient may have been asymptomatic in their childhood or adolescence.⁸

There are many different surgical options to treat high-grade spondylolithesis.^{10,17-25,29} Decompression alone without fusion results in increased postoperative slippage. Therefore, the consensus is to perform spinal fusion. However, surgical approach, fusion levels, and slip reduction remain controversial.

Spinal Deformity Study Group (SDSG) has advocated a new classification for spondylolisthesis. Some sagittal alignment concepts should be included in this chapter for strategies of surgery according to this classification may be varied.⁴⁰

In Situ Spinal Fusion

In situ posterior spinal fusion, which has the advantage of less neurologic injury, has been recommended in some reports.²⁶⁻²⁸ Direct comparison of in situ fusion and fusion with reduction suggests that functional and clinical outcomes are equivalent, with a lower risk of neurologic injury for patients not undergoing reduction.^{27,28} However, major problems associated with in situ fusion are as follows:

(1) a high prevalence of pseudarthrosis, (2) progression of spondylolisthesis after surgery, (3) cauda equina syndrome despite successful solid bony fusion, (4) residual cosmetic deformity, (5) lumbosacral deformity resulting in sagittal imbalance, and (6) a small possibility of iatrogenic nerve root injury.

FUSION WITH REDUCTION

Some recent reports have recommended posterior correction and fusion using instrumentation, and this technique has gained popularity because of the ability to attain rigid fusion with good postoperative sagittal balance.^{24,25,30} Lamartina et al.²⁹ emphasized the restoration of sagittal balance being more important than reducing the vertebral slip. They reviewed the published cases of patients who underwent substantial reduction for high-grade spondylolisthesis. A total of 12.5% of patients experienced neurological deficits postoperatively, but most (71.4%) were transient.

In high-grade spondylolisthesis, a congenital sacral anomaly or secondary deformity contributes to the mechanical instability at the lumbosacral junction. Anterior reconstruction with a fibular strut graft or interbody cage is necessary because anatomic factors, such as trapezoidal L5 vertebral body or rounded sacral dome, may contribute to failure of fusion. Petraco and colleagues showed in a cadaver study that 71% of the total L5 nerve strain occurs during the second half of reduction.³¹ Thus, they recommended partial reduction because it is safer than complete reduction. Furthermore, they revealed that the correction of lumbosacral kyphosis in high-grade spondylolisthesis relaxes the L5 nerve root and may be neuroprotective. Restoration of the slip angle with partial reduction has been also recommended in other reports.^{17,30-34} We recommend that the slip be reduced to under 25% to obtain enough space for interbody fusion and that the slip angle be restored as much as possible.

Grade V spondylolisthesis, or spondyloptosis, is rare and carries a higher risk of nerve injury. In patients with spondyloptosis, the L5 body is completely translated anteriorly and/or inferiorly slipped below the sacrum. Surgical treatment for this unusual deformity can be challenging. Fusion without reduction using a fibular strut graft, as described by Smith and Bohlman, has a lower risk of iatrogenic nerve root injury when compared to fusion with reduction.³⁵ Gaines and Nichols described a two-stage operation, involving complete removal of the L5 body

anteriorly, followed by posterior reduction of the spondylolisthesis.¹⁸ Although spinal realignment and neurologic improvement were achieved, 77% of patients had some temporary L5 root deficit at long-term follow-up.³⁶ Recently, Kalra et al.¹⁰ introduced a modified Gaines procedure, which is similar to the original method except that they resected only the lower half of L5 anteriorly to avoid excessive shorting of the thecal sac. Resection of the sacral dome which is a shortening osteotomy of the spine allows a single-stage reduction of L5 without lengthening of the lumbosacral region is another choice in patients who have high grade spondylolisthesis.⁴¹

SURGICAL TECHNIQUES

Optimal fusion levels, L4 to S1 versus L5 to S1, for severe spondylolisthesis remain controversial. Kyphosis correction using L4 pedicle screws has been advocated by some authors.^{24,37,38} In our experience,³⁹ there was no significant difference in the correction rate between an L5 to S1 fusion group and an L4 to S1 group. However, operation time was shorter and there was less estimated blood loss in the L5-S1 group. Therefore, we now perform one-stage posterior correction at L5-S1 and save the L4-L5 motion segment. Although some authors recommend a plate system, we prefer a rod-and-pedicle screw construct because it is easy to apply distraction and compression forces. Our surgical techniques are as follows:

1. The patient is positioned prone with maximum hip extension on a radiolucent Hall frame (Fig. 83.2). Positioning is very important to reduce the deformity and to create lumbar lordosis. If the L5-S1 segment is mobile, this corrects the slip angle and pelvic retroversion. The patient's knees should be flexed on a cushion to reduce nerve root tension. At this point, neuromonitoring is performed to determine the baseline status, especially for the *tibialis anterior* and *extensor hallucis longus*, which are often innervated by the L5 nerve root. If the patient complains of radicular pain or motor weakness, the laterality on both sides is carefully checked.
2. An image intensifier is positioned to obtain an accurate lateral view of the lumbar spine. Insertion of L5 pedicle screws is difficult because the L5 vertebra is deep anteriorly.
3. Using the midline posterior approach, the L5 to S2 segments are widely exposed. The presence of spina bifida occulta is carefully determined on preoperative



Fig. 83.2: The patient is positioned prone, with maximum hip extension.

radiographs. If the patient has spina bifida occulta, subosteal exposure around the midline of the sacrum is carefully performed to avoid an incidental durotomy. Exposure lateral to the transverse processes is usually difficult due to the anterior L5 vertebral body slippage. Although it is difficult to expose the whole transverse process, proceeding ventrally along the interarticular process helps to identify it.

4. First, complete L5 laminectomy is performed. If there is spondylolysis, Gill laminectomy is performed. Fibrocartilaginous tissue and ragged bone from the area of the lysis edge are removed with Kerrison rongeurs and curettes. Some of the fibrocartilaginous tissue may extend into the foramen, and this should be removed completely. Next, partial S1 laminectomy is performed. The L5 nerve root should be exposed as far laterally as possible to ensure adequate visualization (Fig. 83.3). Occasionally, the L5 nerve roots are difficult to identify because of severe slippage. The foramen is decompressed along the L5 nerve root tract.
5. To obtain sufficient correction, pedicle screws need to be precisely inserted. Fluoroscopic guidance is, therefore, used to place all the pedicle screws. In particular, the S1 pedicle screws are placed cephalad from a slightly caudal starting point, which allow us to obtain a long lever arm during reduction (Fig. 83.4). Accurate insertion into the promontorium leads to tricortical purchase. Although some authors recommend a plate system, we prefer a rod system, which permits the application of distraction and compression forces.

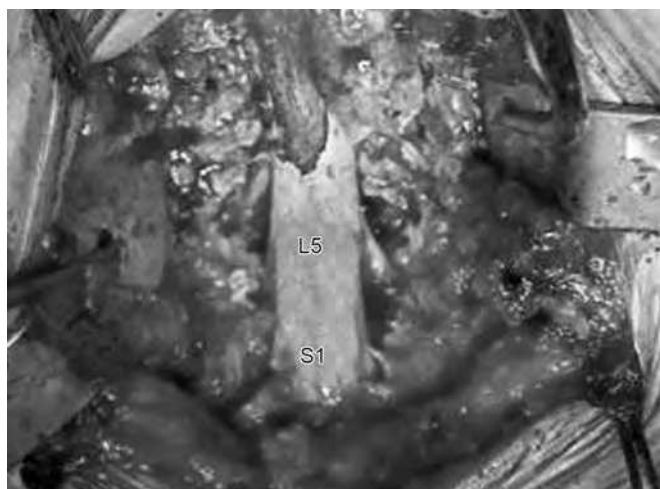


Fig. 83.3: The L5 and S1 wide laminectomy is performed to observe the nerve root during reduction.



Fig. 83.4: Pedicle screw insertion is guided by fluoroscopy.



Fig. 83.5: Both lordosis rods are placed before reduction.



Fig. 83.6: Nuts are installed gradually on L5 pedicle screws with distraction forces.

6. The L5-S1 intervertebral disc is incised with a knife and removed with an intervertebral disc shaver. The disc space is usually narrow. The purpose of disc resection is to release the anterior elements at this point. Wide resection of the intervertebral disc should be performed to avoid L5 impingement by posterior disc bulging during reduction.
7. A rod with sufficient lordosis is applied to the pedicle screws (Fig. 83.5). Nuts are installed and tightened on the S1 pedicle screws. Nuts are also installed on the L5 pedicle screws, but tightened gradually, while distraction forces are gently applied to both rods (Fig. 83.6) under motor evoked potential (MEP) and/or

sensory evoked potential (SEP) monitoring. Combined EMG, SEP, and MEP monitor is advocated in SDSG. Some authors have indicated that too much distraction force may injure the L5 nerve root because of excessive tension. This maneuver eases the reduction of the L5 vertebra, which has slipped anteriorly with a rotatory movement, and widens the foraminal space. Recently, a spondylolisthesis reduction instrument that can lift the L5 using cycloid force became available for cases of severe slippage (Fig. 83.7). Regardless, the reduction maneuver can potentially injure the nerve root. Therefore, careful neurophysiological monitoring and visual inspection of the L5 nerve root are mandatory.

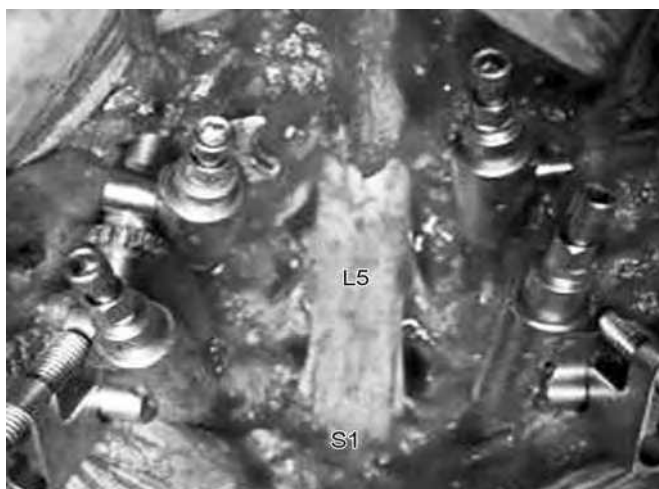


Fig. 83.7: A spondylolisthesis reduction instrument can lift L5 using cycloid force.



Fig. 83.8: After interbody cage insertion, compression force is applied.

8. After the correction, disc resection is performed again. The rounded S1 superior end plate is removed by an osteotome. Interbody cages made of titanium alloy or polyetheretherketone are inserted bilaterally. The intervertebral space is filled with iliac crest autograft. Finally, compression force is applied to obtain lumbar lordosis between the L5 and S1 pedicle screws (Fig. 83.8). After reduction, it is usually easy to observe the L5 nerve root, which should be carefully checked for foraminal impingement.
9. After surgery, the patient is kept in a supine position for 2 or 3 days and wears a hard brace for 8-12 weeks.

CASE PRESENTATION

A 41-year-old woman complained of persistent low-back pain and severe bilateral thigh pain for 1 year. She had had occasional low-back pain in her late teenage years. The clinical symptoms had been relieved by conservative treatment with a brace and analgesics. However, the pain had worsened, and she was unable to stand without assistance at the initial visit.

She complained of low-back pain and left buttock to posterior thigh pain when standing and at rest. There was severe tightness of the hamstrings. There was no motor or sensory deficit or pathological reflex, but she had experienced some episodes of frequent urination. The preoperative Japan Orthopaedic Association (JOA) score was 17/29.



Fig. 83.9: A 41-year-old woman complained of persistent low-back pain and thigh pain. Radiography revealed high-grade spondylolisthesis (slip angle: 38°, slip percent: 63%).

The radiographs revealed high-grade spondylolisthesis (slip angle: 38°, slip percent: 63%) (Fig. 83.9). Monosegmental fusion and reduction with neuromonitoring and image guidance was performed. No operative complications, including nerve root impairment, occurred. The operation time was 4 hours and 45 minutes. The estimated blood loss was 360 mL. Postoperatively, the low-back pain and preoperative neurological deficit had resolved, and the JOA score improved to 25/29. The slip angle was corrected to 3°. The percent slip was corrected to 3% (Fig. 83.10).

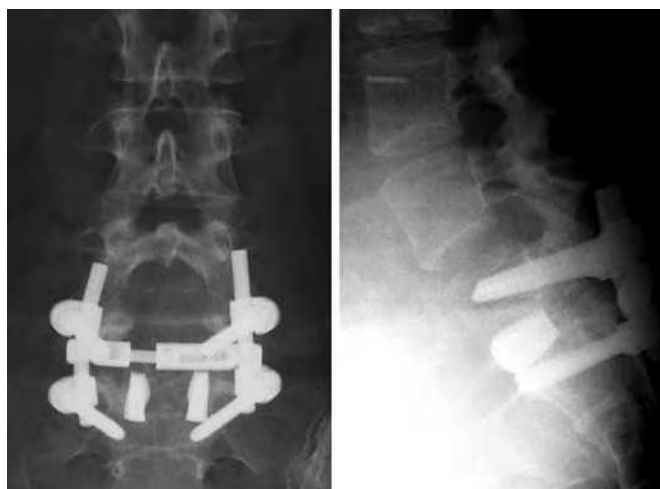


Fig. 83.10: The L5-S1 fusion with reduction was performed. Percent slip was corrected to 3%.

KEY POINTS

- Surgical treatment for high-grade spondylolisthesis is challenging.
- Precise instrumentation and neuromonitoring are necessary in the surgical treatment of high-grade spondylolisthesis.
- Wide laminectomy and exposure of the L5 nerve root are needed to avoid intraoperative nerve root impingement.
- The slip should be reduced to within 25% and the slip angle should be restored as much as possible.
- Monosegmental fusion using a modern pedicle screw system and interbody cage enables favorable correction and fusion.

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Nonoperative Treatment of Fractures of the Thoracolumbar Spine

FC Oner, Agnita Stadhouder, Wilco Jacobs

Snapshot

- » Diagnosis
- » Classification
- » Conservative Treatment
- » Future Research

INTRODUCTION

Hu et al. found an average annual incidence of 64 patients with a thoracolumbar spinal fracture per 100,000 with an annual hospitalization rate of 29 per 100,000 in Manitoba, Canada.¹ An epidemiological study performed in Sweden showed an incidence of thoracolumbar fractures of 30 per 100,000 inhabitants per year. When patients older than 60 years were excluded, the incidence was 13 per 100,000. The most frequent causes were transport accidents and falls from heights.² A large epidemiological study in China between 2001 to 2007 showed that 4.58% of all traumas were thoracolumbar spinal fractures, with an annual increase in incidence each year. The two most common causes of injury were traffic accidents and falls from height.³ A review on road traffic injuries shows that in high-income countries, the number of lives lost in road crashes indicates a downward trend. On the other hand, the best available evidence suggests that in low-income and middle-income countries, the incidence of road traffic injuries is higher and still growing. Using the best available evidence, the World Bank report estimates that there will be a 28% reduction of fatalities in high-income countries in the next 20 years, while India and China will show an anticipated rise of 92% and 147% of traffic road casualties. Still, estimates are unreliable so far.⁴ The most vulnerable road users are pedestrians, cyclists or users of motorized two-wheelers according to a road traffic report from the World Health Organization.⁵ Together with the rising

incidence of road traffic injuries, the incidence of spinal fractures will proportionately rise. Because spinal fractures have a poor outcome compared with other major injuries, prevention of these traumas is important and policy makers should be aware of this.

DIAGNOSIS

Dependent of trauma cause, patients with a possible spinal fracture are presented at an emergency department on a spine board. After primary Advanced Trauma Life Support (ATLS) survey and stabilization of the spine, the patient is examined by a log roll and inspection of the back. A comprehensive neurological examination should always be part of the physical exam and be recorded, preferably using the systematic approach proposed by the American Spinal Injury Association (ASIA).⁶ Then standard plain film radiography is performed. In polytrauma patients, a Spiral Computed Tomography (SCT) scan is in most hospitals the standard procedure to examine thorax, abdomen, pelvis and spinal injuries as well. On a plain radiography, 25% of burst fractures are misdiagnosed as compression fractures.⁷ A study by Venkatesam showed that especially patients with a high Injury Severity Score, a low Glasgow Coma Scale and hemodynamic instability were most likely to have a thoracolumbar fracture without typical clinical findings and would benefit most from SCT. They also showed that in 303 blunt torso trauma patients, 3.6% of the patients had severe thoracolumbar spinal

fractures without evident clinical findings. This may be due to patient factors but also because of junior staff members performing physical examination.⁸ Further, the sensitivity of SCT detecting spinal fractures is 100% compared to 70% in plain film radiography and, on the contrary of what is expected, the radiation dose in thoracolumbar spine is lower with SCT (13 mSv compared to 26 mSv) than with plain films. SCT is far more costly than plain film radiography but there is a similar mean overall spinal imaging cost per patient (\$172 vs \$164) when time in the radiology department is considered.⁹

Magnetic Resonance Imaging (MRI) is more frequently performed in cervical injuries and may be indicated in certain cases of thoracolumbar trauma. Besides the cases with neurologic deficit, MRI is also helpful to evaluate the integrity of the so-called posterior ligamentous complex (PLC) (supraspinous and interspinous ligaments, ligamentum flavum, facet capsules and thoracolumbar fascia), which is an important factor for decision on treatment. The sensitivity of MRI for diagnosing injury of the various components of the PLC ranged from 79–90%. The specificity ranged from 53–65% with a positive predictive value of 70–78% and a negative predictive value of 50–88%.¹⁰ In patients with an ASIA score of A–C, the predictive values were higher and Vaccaro concluded that the integrity of the PLC should not be used in isolation to determine treatment.¹⁰

Three-dimensional CT can show more details of posterior element injured, which is the indirect sign of PLC. The most widely used sensitivity series of MRI is T2 short tau inversion recovery (STIR) or FAT SAT sequencing. Missed STIR scan sometimes may miss PLC injury, which contributes to prevent secondary kyphosis after anterior column injury.¹¹

CLASSIFICATION

More than 60 different classification schemes have been reported in the literature. The comprehensive classification scheme proposed by Magerl et al.¹² is the most systematic scheme for a general understanding of the injury types. In this scheme, there are three basic types of injury:

- **Type A:** Injury to the anterior elements (vertebral body and the discus) predominantly by compression forces. The posterior tension band is intact. Sub-classification:
 - **A1:** Wedge-compression of the endplate
 - **A2:** Split fracture of the vertebral body
 - **A3:** Burst fracture – fracture of the endplate with involvement of the canal.
- **Type B:** In addition to injury to the anterior elements, there is also failure of the posterior tension-band.
- **Type C:** As a result of injury to the anterior and posterior elements, there is a displacement/dislocation (Fig. 84.1).

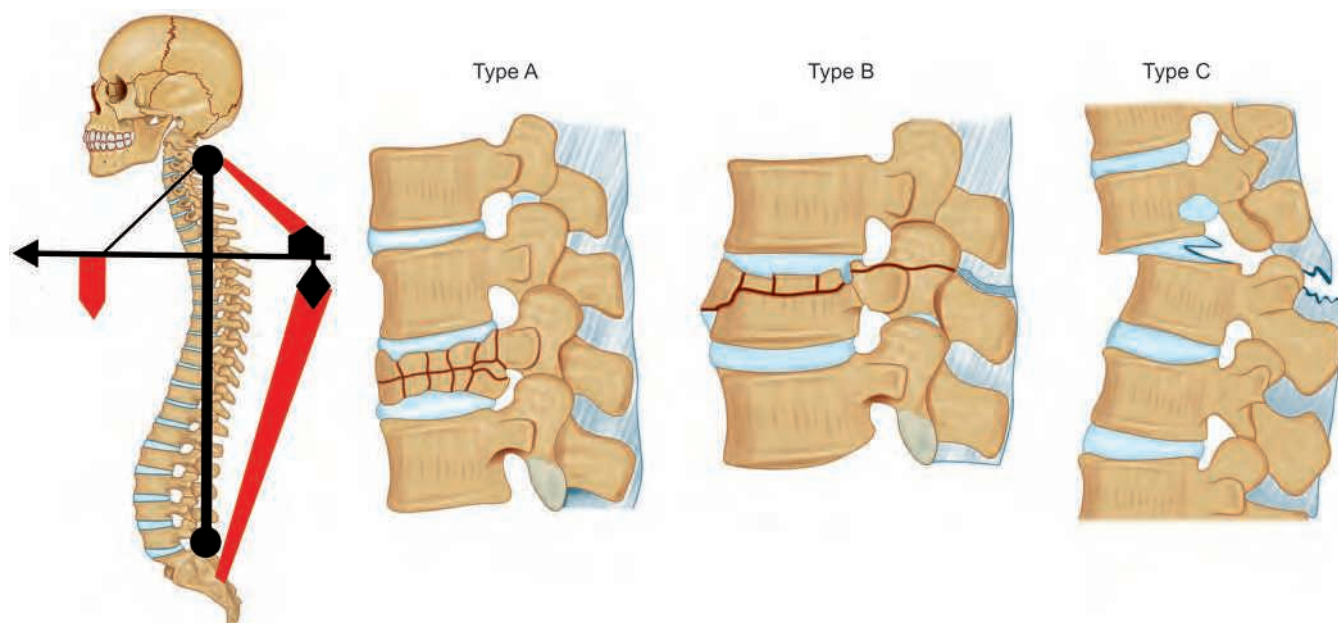


Fig. 84.1: Basic types according to the AO Classification. Type A fractures compression injuries of the anterior elements with intact posterior tension band. Type B fractures with ruptured tension band. Type C fractures dislocation and rotation.

The Spine Trauma Study Group (STSG) has developed a thoracolumbar injury severity and classification system (TLICS), which can be used to decide on the most appropriate treatment.¹³ The following items are evaluated and points are assigned:

- **Morphology:**
 - Compression 1 point
 - Burst 2 points
 - Rotation/translation 3 points
 - Distraction 4 points
- **PLC (posterior ligamentary complex = tension-band):**
 - Spinal cord/conus
 - Intact 0 point
 - Suspected 2 points
 - Disrupted 3 points
- **Neurology:**
 - Intact 0 point
 - Root 2 points
 - Spinal cord/conus
 - Complete 2 points
 - Incomplete 3 points
 - Cauda equina 3 points

The sum of the points from each of these three items makes the total TLICS score.

The treatment algorithm proposed by the STSG:

- TLICS score 1–3: Conservative
- TLICS score 4: Operative or conservative
- TLICS score 5 or more: Operative.

Clinical modifiers such as polytrauma, ankylosis of the spine or the degree of deformity may add up to the basic TLICS score in the decision for conservative or operative treatment.

■ CONSERVATIVE TREATMENT

History

The conservative treatment of spinal fractures has a long history and the first written records date from 3,000 BC with the description of a cervical spinal dislocation with neurological impairment in the Edwin Smith Surgical Papyrus from ancient Egypt. There is also an incomplete description of a thoracolumbar fracture treatment advice in this manuscript. Between these and the writings of Hippocrates (460–377 BC) there are no written documents about spinal injuries. Hippocrates describes two methods

of treatment: shaking on a ladder and traction of the spine on a special bench, his preferred method. In the Middle Ages, the Islamic surgeons Ibn Sina (Avicenna) and Abu Al-Qasim (Abulcasis) continued the Hippocratic tradition. In the modern times, there was growing attention for the treatment of spinal injuries, and in the second half of the 19th century, splinting of the spine was introduced for the prevention of deformity. The last decade of the nineteenth century witnessed a milestone in the diagnosis and treatment of spinal fractures by the development of the ‘X-rays’ by Röntgen in 1895. In the first half of the twentieth century, Lorenz Böhler, a German military surgeon wrote his famous book on traumatology “Techniek der Knochenbehandlung”. He proposed a standard treatment for all thoracolumbar fractures based on “Einrichten, Festhalten, Üben” (reduction, immobilization and exercise). Reduction of the fracture was performed by hyperextension, and then a plaster of Paris corset was applied in this position for immobilization. The treatment was continued by a standardized training program to avoid muscle loss and improve psychological well-being.¹⁴ Watson-Jones,¹⁵ an influential British trauma surgeon, subscribed and popularized the ideas of Böhler in the 1940s, although there was some evidence also in that time that a good clinical result did not always correlate with a good anatomical reduction as reported by another British surgeon, Nicoll in 1949.¹⁶

Present

Although conservative treatment of thoracolumbar fractures seems to be a good established treatment modality nowadays, there are still numerous controversies in the literature. One of the major causes for this is that reliable evidence based on good clinical research in spinal trauma patients is still lacking. First of all, there is no agreement on what constitutes a good outcome in spinal trauma patients, especially for those without neurologic involvement. Little work has been done on developing and validating outcome assessments in spinal trauma patients.

While many surgeons agree that patients with neurologic involvement or severe mechanical instability, such as fracture-dislocations, should be treated operatively, spinal fractures categorized as Type A, according to Magerl Classification, may be managed non-operatively—these commonly include the anterior wedge and burst type fractures with intact PLC.

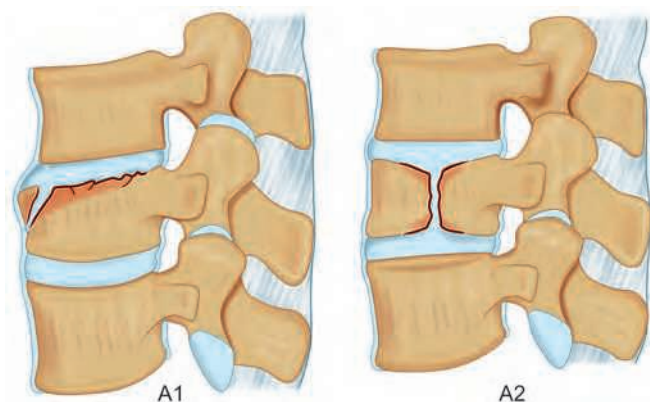


Fig. 84.2: Wedge compression fractures (A1 according to the AO Classification). Fracture of a single endplate without involvement of the posterior wall of the vertebral body. The vertebral canal is intact.

Anterior Wedge and Split Fractures

Nonoperative treatment for anterior wedge-compression (A1) and split (A2) type spine fractures is considered to be safe with an acceptable long-term outcome concerning pain, employability and residual deformity for the majority of patients (Fig. 84.2).

Treatment options vary from bed rest, the use of various orthoses, to functional treatment with postural instructions by physiotherapists. However, there is no consensus in the literature about the optimal management. There is also a paucity of evidence of the effectiveness of any of these different treatment schemes. Various authors concluded that it is not necessary to wear a brace, as this provided no additional therapeutic benefit.^{17,18} Gertzbein in his multicenter spine fracture study saw that after 1 year follow-up patients with a kyphotic deformity of $> 30^\circ$ had an increased incidence of moderate to severe pain.¹⁹ This report seems to be of influence in all further clinical research in the sense that conservative treatment of spinal fractures is reserved for fractures with an initial kyphotic deformity of $< 30^\circ$. The question is whether these patients had only simple wedge-compression fractures or also unrecognized PLC injuries, and were thus actually surgical candidates. Schnake et al. reported that 29% of all type B1 injuries cannot be detected on the X-ray or CT scan in his retrospective study.²⁰ It was argued that if there is $> 50\%$ loss of anterior vertebral height acutely, this may be suggestive of posterior element disruption and, therefore, should be an indication for further investigation.²¹ Despite these

reports and the practice to treat compression fractures usually with 'benign neglect', every spine surgeon knows cases of dissatisfied patients with substantial residual pain after different kinds of nonoperative treatment schemes who occasionally require operative intervention. The reason for this persistent severe pain after relatively minor injuries is not clear. Damaged discs and facet joints may be the pain generators. In split (A2) fractures, avascular necrosis of the anterior part of the vertebral body can occur. However, there is no reliable evidence in the literature on the specific prognosis of these injuries. Whether the disturbance of sagittal balance plays a role is not properly studied yet.

Therapy

The primary goal of treatment for patients with a spinal fracture is to protect the neural tissues and create an environment for optimal functional recovery with minimal pain. Further, the treatment should be cost-effective on the short, but also on the longer term. The majority of the victims are young people indicating that longer-term costs to the society with residual disabilities may be substantial. For wedge-compression fractures, it is not clear whether any active treatment except proper pain management is indicated. There are multiple braces, such as custom-molded total contact orthoses (thoracic-lumbar-sacral-orthosis—TLSO) or prefabricated stiff or elastic braces, which can be used for temporary immobilization. Various authors looked at the effect of braces on the immobilization of the spine. The advantage of a custom-molded cast or TLSO is that it distributes forces over a large surface area, improves fixation of the pelvis and thorax and controls lateral bending and axial rotation (Figs. 84.3 to 84.5).

This is most effective in immobilizing the spinal column.²² The prefabricated Jewett brace has no pelvic support and, therefore, lateral and axial rotations are not prevented (Fig. 84.6).

This brace is, thus, only indicated for fractures that are caused by flexion injuries like a wedge-compression fracture. The level of fractures for which this brace is recommended is from T6 to L3 with emphasis on the thoracolumbar junction.

Outcome of Anterior Wedge Fractures

There is one randomized clinical trial comparing physical therapy, a thermoplastic removable brace and a plaster cast for 6 weeks. Patients with less than 50% loss of

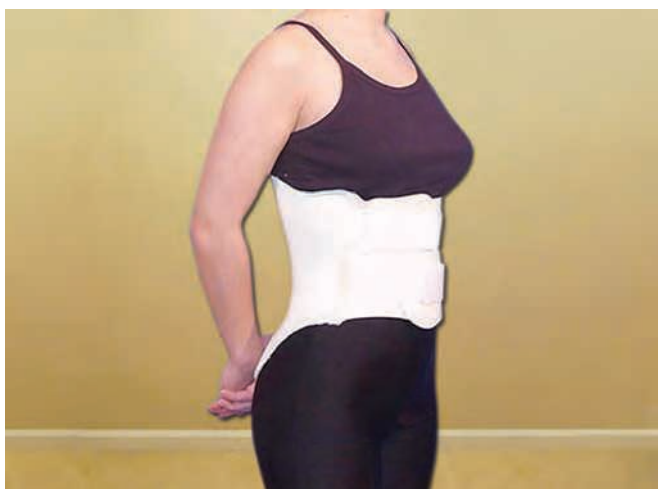


Fig. 84.3: Lumbosacral orthosis.

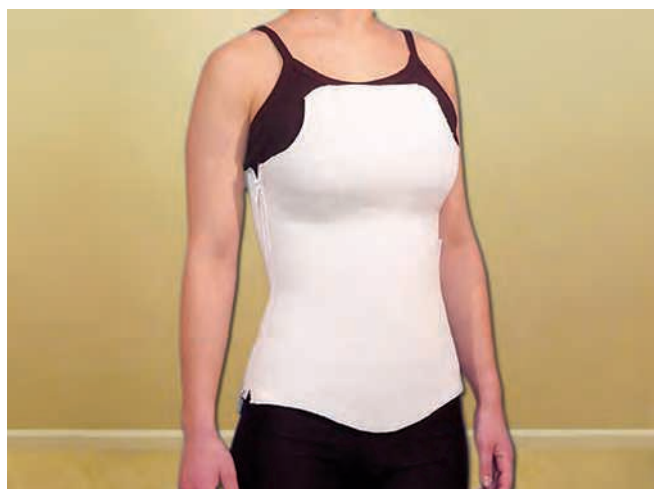


Fig. 84.4: 3-point orthosis.

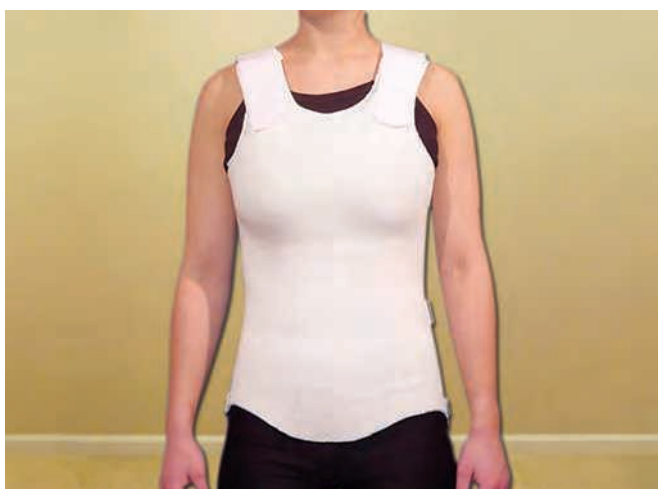


Fig. 84.5: 4-point orthosis.



Fig. 84.6: Jewett brace.

anterior height were included. In this study, some type of immobilization was found to be better than physical therapy alone, considering Oswestry Disability outcome and Visual Analog Scale (VAS) pain score after an average follow-up of 7 years.²³ In this study, 18% of patients complained of moderate to severe persistent pain. Folman performed a retrospective analysis of patients with a thoracolumbar fracture (T11-L2) with at least 3 years' follow-up. Half of the patients were treated with a 3-point brace for 5 weeks and half with physical therapy. In this group, mild to moderate chronic low back pain was reported in 69% of cases and 25% had changed jobs, mostly full-time to part-time. These authors could not

find any effect of immobilization on the long-term on clinical results.²⁴

Karjalainen looked at patients treated with or without an extension brace ($n = 21$ vs 105 patients) after 7 years. There was no difference in outcome concerning radiological or functional aspects. In the brace, 19% had a poor outcome, in the functional group 17%.²⁵

A systematic review in 2009 did not find any effect of bracing in 7 retrospective studies.²⁶

In summary, anterior compression fractures can be treated in a functional way, where physical therapy and/or a simple brace can be considered for initial pain management. If there is compression of the anterior part of the

vertebra of more than 50% or a kyphosis angle more than 30°, PLC injury should be excluded and, if present, operative treatment considered.

One should not forget that many of these patients end up with some degree of persistent back pain and disability even after these relatively minor injuries. This incidence is much higher than seen after comparable injuries to the extremities. Almost 20% of patients suffering from moderate to severe pain after a 'minor' injury of the ankle, knee or wrist would not be accepted as 'good results.' We should ask ourselves how we can predict these unsatisfactory results and whether we can prevent disability.

Burst Fractures

Burst fractures are characterized by failure of the endplate under compression causing a fracture with involvement of the posterior cortex of the vertebral body, leading to a loss of integrity of the spinal canal (Fig. 84.7).

There may be varying degrees of canal involvement and compression of the dural sac with possible neurologic injury. Most burst fractures occur at the thoracolumbar junction (T10-L2) probably because of the transition of the kyphotic immobile thoracic spine to the lordotic mobile lumbar spine.

Burst fractures can be 'incomplete' involving only a single end-plate or 'complete' with fracture of the whole vertebral body and both endplates. It is not clear whether this distinction between 'complete' and 'incomplete' burst fractures has any prognostic significance despite the weak evidence from studies using the 'load-sharing classification'.²⁷ Burst fractures can also be associated with injury

to the posterior tension band or posterior ligamentous complex (PLC). Many surgeons recommend that when PLC injury is present, operative treatment is the preferred method in order to prevent progressive deformity or worsening of neurology.^{13,28}

Therapy

There is no consensus on the proper treatment of burst fractures of the thoracolumbar spine without neurologic deficit or PLC injury. There is a high degree of variation in the practices between different countries and regions. The same kind of fracture can be treated surgically with circumferential fusion in one region, while it may get a conservative care even without using a brace in another. Lacking universal tools for classification and outcome, it is not at this moment possible to provide strong evidence-based recommendations on the treatment of these relatively common injuries.

Many different nonsurgical treatment methods have been described in the literature for treatment of thoracolumbar fractures varying from bed rest in a plaster cast to mobilization without a brace. In the early 20th century, conservative treatment of serious thoracolumbar fractures consisted of bed rest in a plaster cast for up to 3 to 6 months, a treatment method associated with many complications. With the writings of Böhler in 1929, the more functional treatment of thoracolumbar spinal fractures became popular with reduction, plaster cast immobilization and exercises.¹⁴ Nicoll in 1949 advised a protective plaster in the neutral position without attempting a reduction of deformity.¹⁶ In 1970, Holdsworth actually

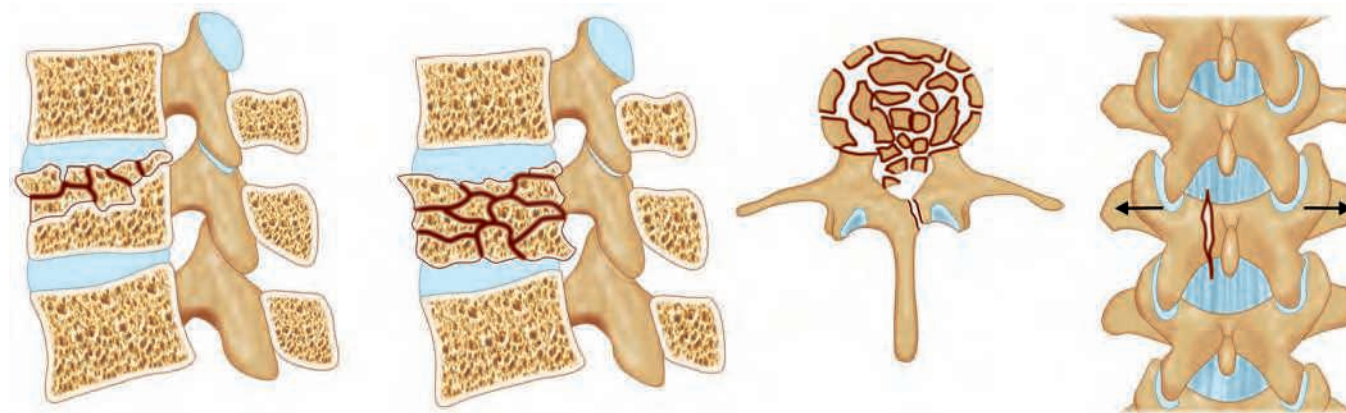


Fig. 84.7: Burst fractures. Fracture of the vertebral body with any involvement of the posterior wall. Vertical fracture of the lamina is usually present and does not indicate a tension band failure. Varying degrees of canal encroachment by fracture fragments.

introduced the concept of ‘burst fracture’ and described it as a stable injury because of intact ligaments. He advised that patients should be immobilized in a plaster with bed rest for 8 to 12 weeks because these fractures were very painful.²⁹ In 1984, Denis treated 39 patients with burst fractures nonoperatively in body casts and reported that 17% of these patients developed neurological complications, an exceptionally high rate not reported in other publications. This publication was influential in the growing popularity of operative treatment.³⁰ All of these reports were retrospective case studies. Cantor was the first to report in 1993 on the results of a prospective study of 33 patients. Only 18 patients were available for follow-up. Their conservative treatment consisted of a total contact extension TLSO for 14–24 weeks and they restricted their inclusion criteria to less than 30° kyphosis and less than 50% loss of anterior height, an inclusion criteria commonly adapted afterwards.^{18,31} From then on, more prospective papers were published with various treatment options, like a hyperextension brace and mobilization³²; 4–6 weeks of bed rest followed by mobilization in a cast³³; reduction under sedation and application of a body cast used for 3 months and mobilization.³⁴ Also two randomized controlled trials comparing operative and conservative treatment were published. In the nonoperative arms, Wood treated patients with a TLSO or a cast after reduction of the fracture for 14 weeks and mobilization;³⁵ Siebenga gave patients a Jewett brace for 3 months.³⁶

Finally, in 2009, the results of a prospective randomized multicenter paper were published comparing a prefabricated TLSO for 8–10 weeks compared with no orthosis for the treatment of thoracolumbar spinal fractures,³⁷ which also indicated no difference in Roland-Morris Disability Questionnaire, pain, functional outcome, generic health-related quality of life, sagittal alignment, length of hospital stay, and complications.

As bed rest for burst fractures has not been reported in the last two decades, the spectrum of present-day nonoperative treatment options ranges from reduction (Fig. 84.8) of the fracture followed by immobilization in a cast for three months to a mere functional treatment without any external support.

Outcome of Burst Fractures

Before discussing the outcome of conservative treatment of TL fractures, one should realize that there is no universally accepted way of measuring the outcome of these injuries.



Fig. 84.8: Reduction of fracture.

There is no consensus among the experts on the question of how a good or poor outcome should be defined. Little work has been done on developing and validating outcome assessment instruments in spinal trauma patients. Studies investigating outcomes in (spinal) trauma patients typically use a combination of several outcome measures, or improvise their own measures. Outcome reports in spinal trauma, therefore, should be interpreted cautiously.³⁸ Outcome in trauma patients is relevant in the short-term considering the duration of pain and return to work and other social activities. But also the change in the global spinal sagittal balance may be an important factor in the longer term. These are parameters not studied properly yet. Regional kyphosis angle was studied in the past as a possible critical parameter, but no evidence was found that regional kyphosis angle alone might be strongly related to clinical outcome.³⁹

Tropiano reported on the clinical outcome with reduction cast where 64% of patients did well considering pain, but 36% had moderate or severe pain after a mean follow-up of 3 years.⁴⁰ In a prospective study, patients with AO type 3 burst fracture and < 35° of kyphosis were randomized to treatment with or without a thoracolumbar orthosis. The primary outcome analysis at 3 month and after 1 year did not show any significant difference between the treatment groups with Ronald Morris Disability Questionnaire Scores of 6 and 7 respectively and VAS pain scores of 2.1 and 1.8.³⁷ As mentioned before, most studies performed are retrospective studies with follow-up periods of 1–2 years. Only a few studies mention long-term follow-up of 9 to 27 years.^{39–41} A study by Weinstein showed that after conservative regimens

varying from 3 months' bed rest to mobilization in a cast, 57% of the patients were never pain-free, although 88% returned to their former occupation, and none of them required narcotic medication after a mean follow-up of 20 years (11–55 years). A more recent study with a follow-up of 9.5 years related post-traumatic kyphosis angles to sagittal balance parameters. The patients who could not compensate their kyphotic deformity by increasing their lumbar lordosis and had to straighten other adjacent levels had worse clinical outcome. In this series, 62% of the patients did well while 38% had a fair or poor outcome. Also 19% of patients were not able to return to their previous employment, which is comparable with other studies.⁴¹ Another study reported results of burst fractures, treated in a range of direct mobilization to bed rest, where 22% of patients complained of moderate to severe pain after a follow-up of 27 years (range 23–41 years).⁴²

There is no evidence that nonoperative treatment may frequently lead to neurological deterioration. There is one exception, the report by Denis, where 17% of patients developed neurological complications.³⁰ It is not clear whether these patients had only burst fractures with intact PLC or more serious kind of injuries. Overall, nonoperative treatment is safe and, even in cases with some neurological symptoms, improvement has been reported.^{31,39,40,43}

List data of neurological functional improvement in burst fractures would be more persuasive. Dai reported neurological improvement with conservative treatment in Denis B-type burst fractures. Significant correlation ($P < 0.05$) was found between the load-sharing score on admission and the lost of local kyphosis angle at the final follow-up.⁴⁴ There are three reviews on the conservative management of thoracolumbar burst fractures published to date. Four studies are included in the first review: two RCTs, one quasi-RCT and one controlled clinical trial. Pooled data at follow-up showed mean VAS scores of 2.2, mean Roland Morris Disability Scores of 5.8, and return to work rates of 67%.⁴⁵ The other review included also 'unstable' fractures and compared nonoperative treatment with operative treatment. They concluded that this comparison was impossible with the current literature and higher quality randomized controlled trials are needed.⁴⁶ Dai wrote a comprehensive review in 2007 and concluded that in thoracolumbar burst fractures without neurological impairment, there is no superiority of conservative therapy over operative therapy.⁴⁷

In summary, many ways of nonoperative management of thoracolumbar burst fractures have been described

without any evidence of superiority of one scheme over the others. Bed rest is no longer advocated except may be for the first day(s) as pain relief. The need for closed reduction of the fracture is controversial, as is additional bracing. Closed reduction is difficult to maintain and there is no evidence for a significant effect on the long-term. Although there are concerns about the effect of post-traumatic kyphosis on the sagittal balance there are no guidelines on the degree of acceptable deformity. Concerning the immobilization, there is no consensus on the use of a cast, brace or TLSO or the duration of this treatment. Any kind of immobilization should be essentially seen as part of pain management. In general, the recommendation is a short period of bed rest if necessary, followed by some kind of brace for the first week during mobilization. As some of the PLC injuries can go undetected, it is advisable to obtain standing radiograms in this period. If progression of deformity is seen, surgical intervention should be considered.

FUTURE RESEARCH

First of all, there is much confusion on the classification of the traumatic injuries of the thoracolumbar spine, which prevents comparison of the results of different groups. A simple and reliable universal classification scheme would enable communication and research on the treatment and outcome. Little work has been done to date on the development and validation of outcome assessment in spinal trauma patients. Most studies have either assessed spine injuries from the critical care perspective or focused solely on spinal cord injury (SCI) from the standpoint of rehabilitation medicine. Studies that do investigate outcomes in (spinal) trauma patients typically have to resort to a combination of several outcome measures, or improvise their own measures. A proper spinal trauma injury outcome tool should be a simple and universal focusing on resumption of activities in comparison to pretrauma level of functioning. The spine community should concentrate on developing such a tool in the near future to adequately measure outcome in spinal patients.

Further, the debate about optimal management of thoracic and lumbar fractures continues among spine surgeons. New methods of clinical research should be considered and implemented. As shown in the two RCTs comparing operative versus nonoperative treatment of burst fractures, proper randomization of trauma patients is difficult because of different emergency-related factors leading to

strong selection biases and inadequate power to answer primary questions. Alternative methodologies should be developed to perform research on the outcome of trauma patients. One of the possibilities is the surgeon equipoise method recently suggested for these patients.⁴⁸ As spine registries are becoming popular, the spine community should also consider the trauma patients besides the degenerative and deformity cases in the design of these registries, and the proper research methodology.

KEY POINTS

- The incidence of spinal fractures in low- and middle-income countries will probably rise because of an increase in road traffic injuries. Because spinal fractures have a poor outcome compared with other major injuries, prevention of these traumas is important and policy makers should be aware of this.
- Spiral Computed Tomography shows 100% sensitivity for detecting spinal fractures compares to 70% on plain radiography films. MRI should be used when neurological impairment is present or PLC injury is suspected.
- Anterior compression fractures can be treated in a functional way, where physical therapy and/or a simple brace can be considered for initial pain management. If there is compression of the anterior part of the vertebra more than 50% or a kyphosis angle more than 30°, PLC injury should be excluded and, if present, operative treatment considered. For burst fractures, the recommendation is a short period of bed rest, if necessary, followed by some kind of brace for the first week(s) during mobilization and PLC injury should be excluded.
- There is no consensus on the use of outcome measurements in trauma patients with a spinal fracture. Therefore, good outcome is not defined. In the near future, a proper spinal trauma injury outcome tool should be developed, which is simple and universal, focusing on resumption of activities in comparison to pretrauma level of functioning.
- Appropriate randomization of trauma patients is difficult and alternative research methods should be developed to perform research in trauma patients.
- These patients should be included in patient registries to be able to compare treatment outcome, which leads to evidence-based treatment of these complex patients.

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Surgical Indications and Management of Thoracolumbar Fractures

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Snapshot

- » Epidemiology
- » Anatomic Considerations
- » Clinical Evaluation and Management
- » Physical Examination
- » Imaging
- » Injury Mechanisms and Spinal Stability
- » Indications for Surgery
- » Operative Treatment

INTRODUCTION

Fractures of the thoracic and lumbar spine occur in approximately 6% of patients involved in blunt trauma, with the majority of these injuries occurring at the thoracolumbar junction (T12–L1). The aim of treatment, both nonoperative and operative, is to maintain spinal alignment and stability, preserve neurologic function, and minimize complications. Understanding these basic principles helps us to define the indications for surgery and subsequent management of thoracolumbar injuries.

EPIDEMIOLOGY

The incidence of spine fractures (9–22 cases/1,000 people/year) is stable, but the mechanisms of injury and the patient demographics have shown some changes over the years. Higher energy mechanisms typically affect younger patients, while the elderly with poorer bone quality sustain lower energy injuries. The majority of high-energy injuries occur as a result of motor vehicle collisions and falls from a significant height. Other mechanisms include sports and thrill-seeking activities. Concomitant spine injuries at noncontiguous levels occur in approximately 15% of thoracolumbar fractures. As our general population ages, low-energy injuries become more prevalent, resulting in osteoporotic vertebral compression fractures (OVCF).^{1,2} Roughly 25% of OVCFs present with significant pain

initially, and most can be adequately managed conservatively.³ Treatments of high-energy injuries differ based on the mechanism of injury, fracture pattern, soft tissue injury, and neurologic injury.

ANATOMIC CONSIDERATIONS

The thoracolumbar junction, T11–L2 spinal levels, is particularly susceptible to injury because of some specific anatomic features. Its costovertebral articulations and coronally oriented facet joints, which limit flexion and extension motion, stabilize the thoracic spine. This region of the spine is kyphotic (20–50°) with a relatively narrow spinal canal and therefore unable to accommodate more than minimal canal intrusion upon the neural elements.

Whereas the thoracic spine has greater axial rotation, the lordotic (40–80°) lumbar spine has more flexion and extension capabilities with sagittally oriented facet joints. The L3 vertebra is typically in a neutral position. The thoracolumbar junction represents a shift in the weight-bearing axis from a kyphotic, rigid thoracic spine to a lordotic, mobile lumbar spine with the fulcrum at the T12–L1 intervertebral disk, therefore making this region at higher risk for injury.

The adult spinal cord typically ends at the L1 vertebral body level and may be injured anywhere from the foramen magnum to the thoracolumbar junction. The spinal cord

is perfused by one anterior spinal artery and two posterior spinal arteries, which receive their supply from segmental radicular arteries and, in turn, from the posterior intercostal arteries. In a small percentage of patients, the artery of Adamkiewicz is the dominant anterior radicular artery that originates from one of the left T8–L2 intercostal arteries and therefore provides the major vascular supply to the anterior thoracolumbar spinal cord. An injury to this region may result in a significant vascular insult to the spinal cord.

CLINICAL EVALUATION AND MANAGEMENT

Primary responders should adhere to the systematic universal approach to all trauma patients in the field by securing the airway, ensuring adequate ventilation, and supporting hemodynamic status (ABCs). Patients with a spinal cord injury (SCI) may exhibit neurogenic shock, which is a circulatory collapse due to loss of sympathetic tones. This is identified by bradycardia associated with hypotension in the trauma setting. The patient is immobilized on a rigid backboard using in-line manual traction and a hard cervical collar before transportation. In order to initiate the appropriate algorithm of care, it is critical to appropriately identify the mechanism of injury and initial neurologic status. The patient should then be transported to the nearest facility with the necessary resources to treat acute traumatic spine injuries because optimal outcomes are achieved with a multidisciplinary team approach. In some cases, the trauma team can successfully manage thoracolumbar fractures nonoperatively if there are no dedicated spine specialists at the treatment facility.⁴

PHYSICAL EXAMINATION

The patient should be carefully logrolled into the lateral decubitus position with the cervical spine immobilized, while the back is thoroughly inspected for injuries including contusions, lacerations, tenderness, and step-offs. It has been reported that persistent localized tenderness after trauma to the thoracolumbar spine without obvious radiographic findings is indicative of the underlying occult spinal fracture in 30% of patients. A thorough examination of the neurologic system should include motor, sensory, reflex, and rectal examinations, documented using either the Frankel Impairment Scale or the American Spinal Injury Association (ASIA) form. Motor function is

assessed using the major muscles in the upper and lower extremities and graded on a scale of 0–5. Sensation is assessed in a dermatomal distribution including the perineal region because sacral nerve root sparing (detected by a normal sacral sensation or rectal examination) has been shown to be a positive prognostic factor for potential SCI recovery. The initial ASIA scale score has been shown to be a reliable predictor of long-term outcome in patients with cervical or thoracic SCI.

Injuries to the spinal cord above the level of the conus may result in spinal shock, which is a physiologic disruption of spinal cord-mediated function. This can cause complete absence of all motor, sensory, and reflexes below the level of SCI and typically resolves within 24–48 hours. Because the bulbocavernosus reflex is the first to return (it is the lowest cord-mediated reflex), this can be checked by brief traction on the Foley catheter or applying pressure on the penis or clitoris during a rectal examination resulting in sphincter contraction. If patients are in spinal shock, accurate assessment of neurologic function can only be made once it is resolved because many patients can have spontaneous recovery. Conus medullaris or cauda equina injuries can result in permanent loss of the bulbocavernosus reflex due to injuries of the lower motor neurons involved in the reflex—these patients are not in spinal shock.

In patients with multiple injuries, an altered level of consciousness, or head trauma, a more detailed imaging evaluation should be initiated. Certain patterns of injury such as multiple rib fractures, pulmonary contusion, widened mediastinum, abdominal bruising, visceral injury, and bilateral calcaneus fractures may indicate occult thoracic or lumbar spine trauma. In patients with associated spinal injuries, nearly half of these are missed on initial evaluation that could lead to neurologic injury or progression.

IMAGING

Plain radiographs of the spine should include orthogonal views and can provide a rapid means of screening for trauma including sagittal alignment; however, patients are typically supine, which can underestimate the degree of injury. Standing radiographs allow for weight bearing, which often worsens alignment. A loss of anterior vertebral height >50% suggests significant posterior ligamentous complex (PLC) injury. On the anterior-posterior view, coronal alignment can be assessed. Increased interspinous



Fig. 85.1: Sagittal computed tomography demonstrating the ankylosed spine with an extension-type fracture. This shows the ankylosed spine behaving like a long bone rather than a multiarticulating system of complex joints.

process distance suggests a flexion-type injury, while increased interpedicular distance suggests a burst fracture. A misaligned spinous process may be a rotational injury and focal scoliosis suggests an unstable injury.

Notably though, current literature has moved us away from plain films because of delays in care and inaccuracy in diagnosis.⁵ Advanced imaging modalities, such as magnetic resonance imaging (MRI) or computed tomography (CT), were once reserved to detail injury morphology after screening plain films, but now most trauma protocols use rapid screening helical CT scans of the head, thorax, abdomen, and pelvis during a routine evaluation. The images can then be reformatted to visualize the cervical, thoracic, and lumbar spines. If an injury is detected during the screening process, dedicated 2–3-mm cut axial images of the spine can be obtained and reconstructed. When using plain radiographs, injuries are typically missed in patients with ankylosing spondylitis or obesity and in those patients with fractures at the cervicothoracic and occipital–cervical junction. The CT provides for increased sensitivity, specificity, and predictive value in detecting spinal injury compared with plain radiographs.^{5,6}

CT imaging and its reconstruction formats enable evaluation of canal encroachment and overall alignment (Fig. 85.1). Recently, two studies sought to measure the deformity associated with thoracolumbar fractures with different imaging techniques. The first study looked at the measurement of kyphosis between plain radiographs, CT,

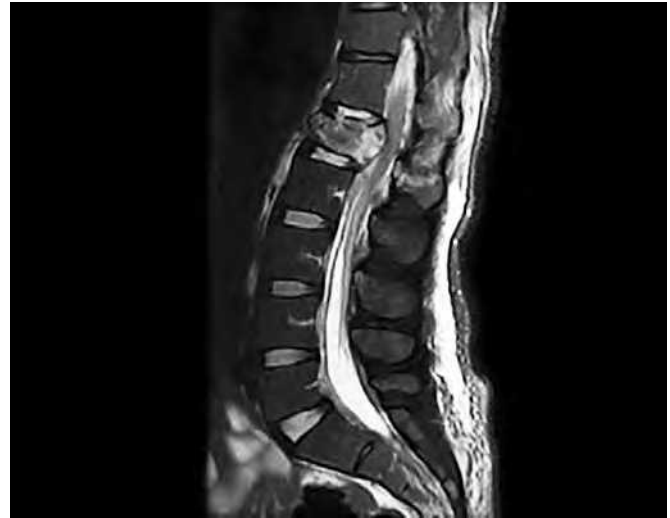


Fig. 85.2: Increased signal in T2-weighted magnetic resonance imaging images at the posterior ligamentous complex represents injury to the posterior stabilizing elements, signifying a more unstable fracture pattern. This injury includes disruption of the supraspinous ligament, ligamentum flavum and the less robust interspinous ligament.

and MRI. The authors found that Cobb angle measurement, Gardner segmental deformity angle, and anterior body compression percentage are reliable measures of thoracolumbar fracture kyphosis with very high interobserver and intraobserver reliability and very high intermodality agreement of plain X-ray with CT.⁷ The second study compared CT scans and plain radiographs in the acute setting and found an average mean difference of -1.13° in the sagittal plane and 0.10° in the coronal plane, resulting in interobserver correlation coefficients among the four observers of 0.913 and 0.953, respectively. Their research therefore found excellent interobserver correlation.⁸

An MRI complements the CT evaluation by assessing the nonosseous structures including the intervertebral disks, ligaments, and perhaps most importantly, the neural elements. Indications for obtaining an MRI include patients with altered mental status or neurologic dysfunction. Visualization of neural element injuries such as the spinal cord may be helpful in predicting neurologic recovery.⁹ Spinal cord hemorrhage and edema, indicated by a bright signal on T2-weighted images, is generally a poor prognosis.^{10,11} An MRI is also useful for detecting ligamentous injuries, especially the posterior structures (Fig. 85.2).^{12–15} This leads to a better understanding of injury severity including spinal instability necessitating possible surgery. A PLC injury indicates damage to one

or more of the following structures: supraspinous ligaments, interspinous ligaments, ligamentum flavum, and facet capsules. A recent study compared a surgeon's and a radiologist's assessment of PLC injuries by MRI. The researchers found that the surgeon was more accurate in interpreting injuries to some PLC components, but the relatively low positive predictive value and specificity for MRI in assessing PLC integrity suggests that both the surgeon and radiologist tend to overdiagnose PLC injury using MRI. This can lead to unnecessary surgeries if only MRI is used for treatment decision making.¹⁶ Disruption of the intervertebral disc similarly can mean injury to the anterior longitudinal ligament, the disc itself, and possibly the posterior longitudinal ligament (PLL). This can be seen as bright signals on T2 images and typically portend a more unstable fracture pattern. Finally, MRI is useful in visualizing bony edema that may be indicative of an occult fracture contributing to preoperative considerations on levels of fixation.

INJURY MECHANISMS AND SPINAL STABILITY

Axial Compression

An axially directed force through the vertebral body may result in fracture of one or both endplates as well as the body itself. A compression fracture is a failure of the anterior column, while a burst fracture also involves the middle column. The amount and trajectory (i.e. sagittal alignment) of axial load may determine column involvement, where the likelihood of a compression fracture increased with a flexion posture, while the chance of burst fracture increased with an extension posture. A more laterally directed force would result in compression on one side and tension on the other causing an asymmetric lateral wedge compression/burst fracture. The posterior column is more likely involved in these instances resulting in focal scoliosis with an increased risk of instability.

Flexion–Distraction (Chance Injuries)

The primary force of injury is distractive with the axis of rotation typically located just within the anterior column or anterior to the vertebral body producing tensile forces on all three columns. The axis can also occur through the middle column producing a compression or burst fracture



Fig. 85.3: Naked facet sign as seen on the axial computed tomography images where one of the facets is “empty,” which is indicative of a dislocated spine.

while distracting the posterior elements. A chance fracture is a failure of the bony elements, while its variants are purely ligamentous or both.

Flexion–Rotation

The most destabilizing force vector is torsional resulting in shearing of the middle and posterior columns while the anterior column collapses under compression. The involvement of all three columns makes this a very unstable injury that may be seen on anteroposterior (AP) plain radiographs as lateral translation. This may be part of the fracture–dislocation spectrum that is discussed later in this section.

Extension

Extension injuries result in failure of the anterior column in tension and compression through the posterior column. A variation is a distractive force through all three columns with potentially significant displacement. These are highly unstable shear-type injuries that are particularly seen in patients with conditions that cause ankylosis (Fig. 85.3) of the adjacent spine segments (i.e. diffuse idiopathic skeletal hyperostosis or ankylosing spondylitis).

Fracture–Dislocation

Fracture–dislocations are typically caused by a combination of force vectors as discussed previously resulting in disruption of all three columns through bony or ligamentous

elements or both. Therefore, there is a significant degree of spinal instability. Any degree of facet disruption, unilateral or bilateral, with possible vertebral body listhesis presents strong consideration of a fracture dislocation (Fig. 85.3). In some cases, the diagnosis is readily apparent with frank facet dislocation and translation of the cephalad vertebral body, while subtle in injuries in which there has been spontaneous reduction of the listhesis and minimal subluxation of a facet. A high index of suspicion is particularly important in those patients who present neurologically intact but have a subtle facet subluxation as this may be a highly unstable fracture dislocation that can quickly result in neurologic compromise.

Gunshot Injuries

Penetrating wounds from gunshots present another mechanism for thoracolumbar fractures that are usually inherently stable and rarely require stabilization. Plain radiographs and CT along with neurologic examination can characterize the injury. The use of MRI is controversial with the potential risk of bullet migration that has been reported, albeit rare.^{17,18}

Spinal Stability

The concept of spinal stability is predicated upon the maintenance of alignment and the prevention of neurologic deterioration. Treatment strategies have evolved with better understanding of the injury mechanisms and their propensity for early or late instability. This is particularly important at the thoracolumbar junction with its transitional anatomy from kyphotic to lordotic segments. The development of classification schemes has attempted to link different fracture characteristics to prognostic factors and hence guide treatment.

Early attempts at classification categorized spinal injuries primarily on morphology (disruption pattern) but lacked reliability in determining stability, while newer classifications attempted to be more inclusive (integrating mechanistic and biomechanical features); however, they were difficult to apply due to their complexity.^{19,20} The most recent attempt to guide treatment algorithm resulted in the thoracolumbar injury classification and severity score (TLICSS).

Thoracolumbar Injury

Classification and Severity Score

The Spine Trauma Study Group sought to incorporate the morphologic and mechanistic aspects of previous systems

Table 85.1: Thoracolumbar injury classification and severity score.

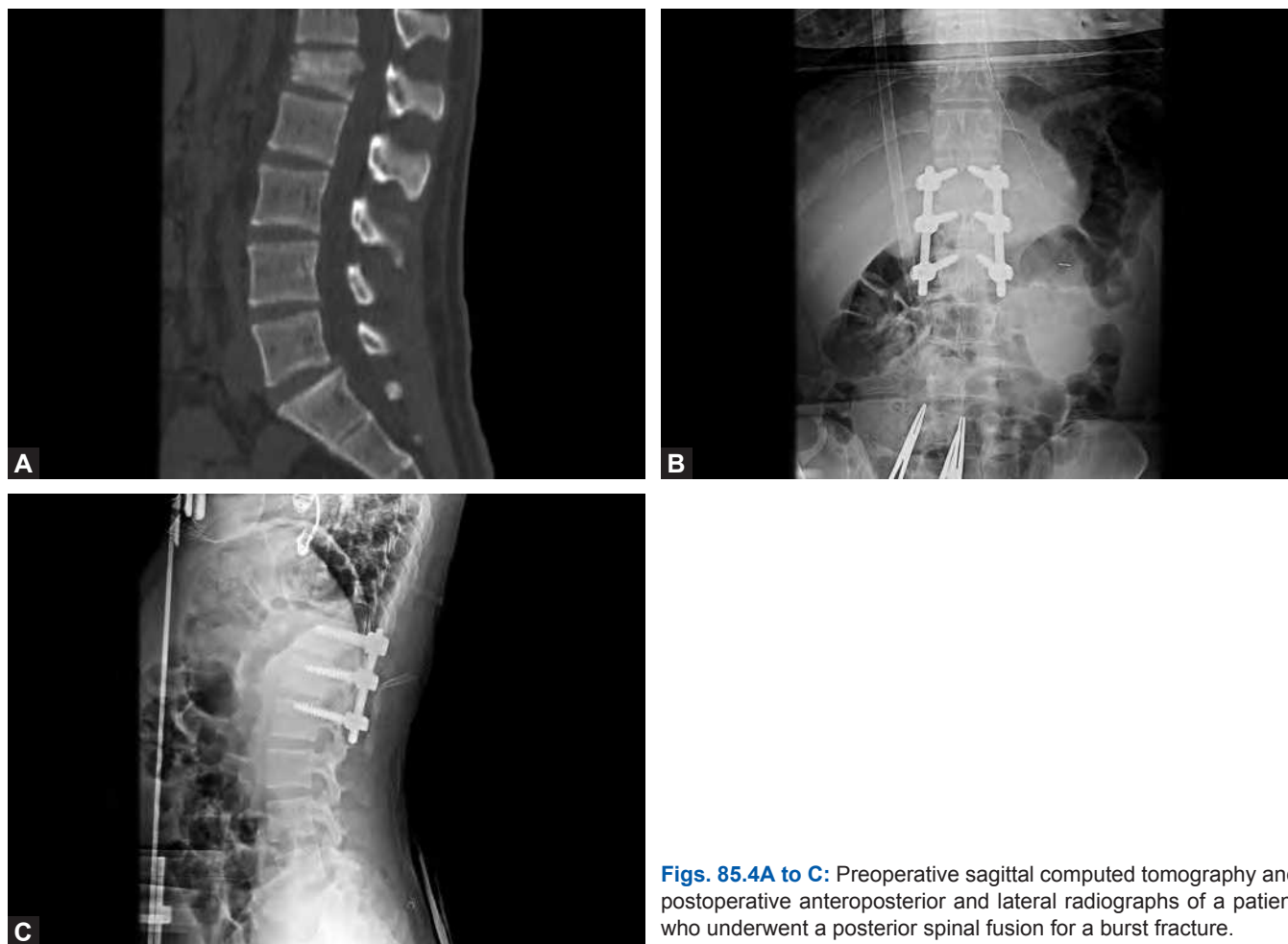
<i>Injury characteristic</i>	<i>Qualifier</i>	<i>Points</i>
Injury morphology	–	
Compression	Burst	+1
Rotation/translation		3
Distraction		4
Neurologic status		
Intact	–	0
Nerve root	–	2
Spinal cord, conus medullaris	Incomplete	3
	Complete	2
Cauda equina	–	3
Posterior ligamentous complex integrity		
Intact	–	0
Suspected/indeterminate	–	2
Disrupted	–	3

with neurologic status to determine stability and guide treatment.

In this system, stability assessment combines fracture morphology, neurologic injury, and PLC integrity (Table 85.1).^{21,22} Points are assigned based on the involvement of each criterion to tabulate a severity score for the patient to determine spinal stability and guide treatment (Figs. 85.4A to C).²³

Fracture morphology has been divided into compression, translation/rotation, or distraction to reflect the mechanism of injury in increasing severity, respectively. In the scoring system of TLICSS, neurologic injury indicates significant instability with incomplete injuries receiving a higher score. PLC integrity is assessed with fat-suppressed T2-weighted MRI with complete disruption likely requiring surgery.¹⁵ Significant instability is noted with a score >4 prompting surgical management, while a score <4 concludes that the injury is amenable to nonoperative measures. A score of 4 does not clearly indicate instability therefore treatment is at the discretion of the surgeon (Table 85.2).

Although this algorithm has not yet been validated by a prospective randomized study, several published papers have evaluated the reliability of TLICSS. In one paper, surgeons agreed with the TLICSS recommendation 96.4% of the time.²⁴ A study performed by an independent group of spine surgeons compared the reliability of the Denis, AO, and TLICSS classification systems and evaluated the skills necessary for their use. They found that the TLICSS system required a base level of knowledge and familiarity to be an acceptably reliable management tool when compared with the Denis and AO systems.²⁵ Another study



Figs. 85.4A to C: Preoperative sagittal computed tomography and postoperative anteroposterior and lateral radiographs of a patient who underwent a posterior spinal fusion for a burst fracture.

Table 85.2: Thoracolumbar injury classification and severity score treatment guide.

Management	Points
Nonsurgical	< 4
Nonsurgical/surgical	4
Surgical	> 4

attempted to validate TLICSS as a guide to management. In a retrospective review of 97 patients, the authors found that TLICSS consistently suggested management similar to past treatment recommendations. The most common exceptions to the TLICSS guidelines involved multilevel contiguous fractures and extension injuries in the ankylosed thoracic spine.²⁶

INDICATIONS FOR SURGERY

Treatment for thoracolumbar fractures can be divided into nonoperative (typically bracing) and operative measures.

Indications for surgery include neurologic compromise, mechanical instability, spinal deformity, and multiple associated injuries. In some cases, determining the appropriate indications is plainly obvious but not so in others, thereby requiring judgment by the treating surgeon. No standard algorithm exists in determining instability on initial presentation. Strong indicators for surgery include patients who have incomplete neurologic injury with significant kyphosis and canal compromise, fracture dislocation, and multiple noncontiguous spinal injuries. Relative indicators include burst fractures with PLC injuries, morbid obesity (and other comorbidities) that make bracing difficult, and multiple injuries that require frequent patient movement. The new scoring method using the TLICSS system may help despite the lack of validation in a prospective randomized study. The goals of any treatment (nonoperative or operative) are to maintain spinal alignment and stability, preserve neurologic function, and minimize complications.

Once the decision to operate is made, the timing of surgery must be considered especially in the multiply injured patient. A systematic review of the literature attempted to determine whether early spinal stabilization (within 72 hours) in thoracolumbar spine trauma decreases morbidity and mortality, by analyzing articles published between January 1990 and December 2008. A total of 68 articles were initially screened, and 9 ultimately met the predetermined inclusion criteria. These studies demonstrated that early stabilization of thoracic fractures reduced the mean number of days on a ventilator, in an intensive care unit, and in the hospital. Early stabilization also reduced respiratory morbidity compared with late stabilization. Except for length of hospital stay, there were no other benefits of early stabilization of lumbar fractures. Based on the evidence available, the effect of early stabilization on mortality could not be determined, but patients with unstable thoracic fractures should undergo early (within 72 hours) stabilization of their injury to reduce morbidity.²⁷

■ OPERATIVE TREATMENT

Anterior Approach

A burst fracture with spinal canal compromise resulting in incomplete neurologic injury is an indication for anterior surgery. A fracture at the thoracolumbar junction may result in injury to the conus medullaris or cauda equina and therefore strong consideration should be made to decompress the canal by complete or partial corpectomy.²⁸ Stabilization can be done with either a cadaveric bone or a cage construct.

Anterior-only surgery can be considered in burst fractures without evidence of PLC injury. Kaneda et al. treated 150 consecutive patients with thoracolumbar burst fractures and associated neurologic deficits with a single-stage anterior decompression, strut grafting, and instrumentation, and achieved a fusion in 140 (93%) patients while 142 patients improved by at least one Frankel grade. The 10 patients with pseudarthrosis were treated successfully with posterior instrumentation and fusion.²⁹ Another study by Sasso et al. reviewed their treatment of 40 patients with anterior-only decompression and reconstruction, and found a 95% fusion rate with a mean improvement in kyphosis from 22.7° to 7.4°. They also found that 91% of their patients with incomplete neurologic injury improved by at least one Frankel grade.³⁰

Posterior Approach

The posterior approach is commonly used to stabilize thoracolumbar fractures (Fig. 85.4) and can be used to decompress as well via an indirect or direct approach. Pedicle screw instrumentation allows for a shorter segment construct compared with prior hook/rod constructs. Several studies have shown though that segmental instrumentation and arthrodesis only one level above and below the fracture yield a >50% failure rate, with resultant progressive kyphosis, loss of anterior vertebral body height or screw breakage.^{31,32} These clinical findings are supported in a review of biomechanical studies that showed increased stress on short posterior segmental instrumentation with loss of anterior column integrity.³³ Short-segment posterior fixation is indicated when combined with anterior column reconstruction or in fracture patterns with minimal anterior column loss. Otherwise, segmental stabilization should be done at two or more levels above and below the injury.

When the PLL is intact, indirect decompression can be done through ligamentotaxis of the fracture fragments via longitudinal distraction. This can be done in compression and burst fractures with an intact PLL, with one study showing an improvement of the mean canal cross-sectional area preoperatively of 49% of normal to 72% of normal immediately postoperatively and a mean cross-sectional area of 87% of normal at 5-year follow-up from remodeling.³⁴

Direct decompression can be done through a transpedicular approach, which would spare the patient from the morbidity of a separate anterior approach, but typically involves the considerable removal of the facet and lamina along with the pedicle. The removal of these posterior bony elements may further destabilize the spine leading to mechanical failure. In a retrospective study involving 28 consecutive patients with a thoracolumbar burst fracture, neural canal decompression was performed via the transpedicular approach, resulting in 82% of patients showing neurologic improvement but at a 17.8% pseudarthrosis rate.³⁵ In another study, anterior column support was performed through a posterior approach. The authors reviewed a consecutive series of 37 thoracolumbar fractures that were managed with three-column reconstruction through single posterior (TRSP) approach between May 2004 and September 2006 and observed them for a minimum of 2 years. The mean operative time was 157 minutes with a mean blood loss of 1086 mL. The average Frankel score improved from 3.46 to 4.46, segmental

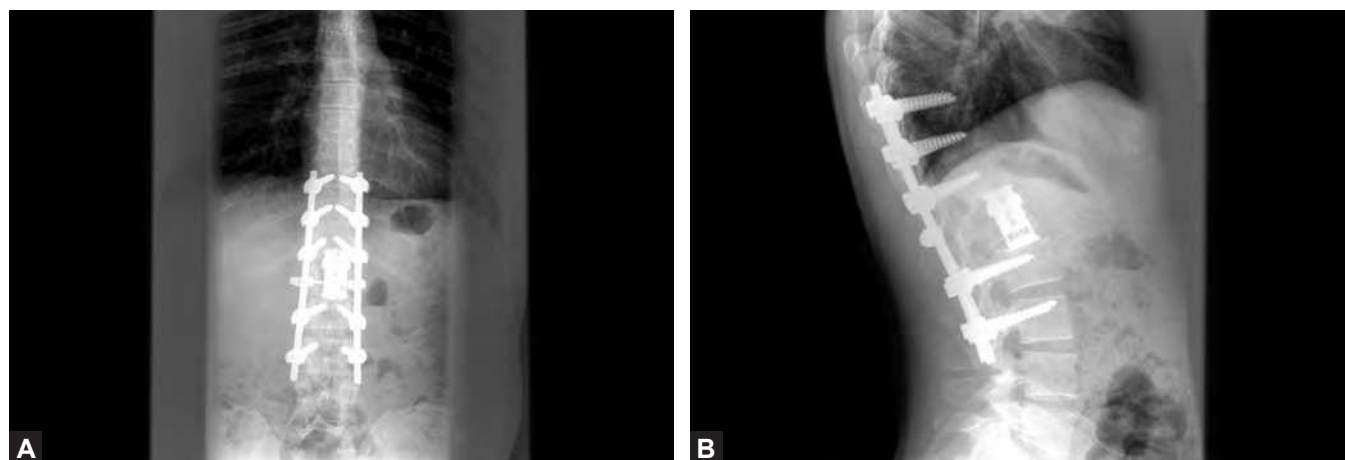
kyphosis improved from 26° before surgery to 5° at the time of the last follow-up, and the loss of segmental height improved from a mean of 35% preoperatively to 7% at the time of the last follow-up. The TRSP approach seems to be a safe and effective option for treating unstable burst fractures.³⁶

Combined Anterior–Posterior Approach

Although there is no clear indication of when to do a combined approach, it is generally believed that loss of anterior column integrity with disruption of the posterior elements provides strong consideration for circumferential fusion (Figs. 85.5A and B). The obvious advantage of this approach is the enhanced mechanical stability of the construct at the expense of the morbidity of two separate approaches that can result in increased complication rates. In vitro studies have shown superior mechanical stability in the combined approach compared with a single anterior or posterior procedure,^{37,38} which has also been seen in retrospective studies with maintenance of kyphosis correction and less instrumentation failure.³⁹ Despite these positive results, there are no prospective studies to validate the combined approach for the different types of unstable thoracolumbar fractures.

Surgical technique—our preferred surgical technique for an unstable L1 burst fracture with conus injury—combined anterior–posterior approach—is as follows:

- Perform the posterior approach first with the patient placed on the Jackson table in the prone position.
- Use somatosensory evoked potentials (SSEP) monitoring for both approaches.
- Make a midline incision from the bottom of T10 down the L2–L3 junction.
- Expose the T11–L3 spinous processes, lamina, and transverse processes.
- Note disruption of the posterior bony and ligamentous elements.
- Place a Kocher at the L1 spinous process and confirm with a lateral X-ray.
- Harvest iliac crest bone graft through a separate incision.
- Insert pedicle screw instrumentation from T11 to L3 (do not place screws in fractured pedicles because there is not much bone purchase and increased risk of neurologic injury).
- Cut and bend appropriate rods into a lordotic posture.
- After placing the rods, apply a cross-link (typically at the fractured level).
- Burr the posterior elements from T11 to L3.
- Morselize the iliac crest autogenous graft and place along the posterolateral gutters.
- Place morselized local autograft and allograft along the lamina bilaterally.
- Obtain final intraoperative X-rays to ensure appropriate instrumentation positioning.
- Place a subfascial drain and then close in standard fashion.
- If postoperative CT reveals inadequate indirect reduction, perform an anterior decompression and instrumentation.
- The vascular team performs the thoracolumbar approach and provides access to the L1 vertebral body, which is confirmed with intraoperative X-rays.



Figs. 85.5A and B: Anteroposterior and lateral radiographs of a patient who underwent a posterior spinal fusion and corpectomy with expandable cage reconstruction for a burst fracture that had a conus medullaris injury.

- Retract the anterior one-third of the psoas muscle anteriorly and the remaining two-thirds posteriorly to allow visualization of the fractured L1 vertebral body.
- Take care to protect the aorta anteriorly and the nerve roots posteriorly while exposing the T12–L1 and L1–L2 disc spaces.
- Perform the discectomies using a 15-blade, Cobb, curettes, and pituitary rongeurs and then identify the T12 inferior endplate and the L2 superior endplate.
- Use an osteotome initially during the corpectomy to cut the L1 vertebral body into multiple fragments and then remove with a pituitary rongeur.
- Use a high-speed burr to thin out the anterior and posterior cortices.
- Use a Kerrison to transect the pedicle and allow exposure of the posterior aspect of the spinal canal.
- Identify the retropulsed fragment(s) and remove with a reverse-angled curette. This should allow complete anterior decompression of the spinal canal.
- Burr the T12 and L2 endplates to slight bleeding bone in preparation of cage placement.
- Place the expandable cage filled with local vertebral body autograft (and harvested rib during exposure) in the center of the corpectomy trough.
- Expand the cage to engage the endplates and then test its stability with the insertion handle (i.e. no movement of the cage).
- Thoroughly irrigate the wound and allow the vascular team to close the wound.

Nonfusion Stabilization Procedures

The concept of an internal brace without fusion for thoracolumbar fractures is gaining popularity in certain practices. The advent of percutaneous techniques has led to the adoption of these principles in treating thoracolumbar fractures in recent years. In a retrospective nonrandomized case-control study, the clinical and radiological results of a minimally invasive posterior technique were compared with conventionally open posterior surgery. Twenty-one consecutive nonrandomized patients with thoracolumbar vertebral body fractures without neurologic deficits were stabilized posteriorly without fusion between 1996 and 1997, and were followed up > 5 years postoperatively. Eleven patients were treated conventionally open, while 10 patients underwent the minimally invasive technique. The patients who underwent the minimally invasive surgery had significantly lower intraoperative blood loss.

There were no differences between the two groups in operative time, X-ray exposure, and the loss of correction. A correlation between the loss of correction and clinical outcome could not be demonstrated. When treating thoracolumbar fractures without neurologic injury, minimally invasive posterior stabilization can lead to lower blood loss in comparison to the conventionally open method.⁴⁰

Another retrospective study was undertaken to evaluate the results of posterior stabilization of thoracolumbar fractures using a nonfusion method (pedicle screw/rod fixation without fusion) and subsequent removal of metal implants after an appropriate time period postoperatively. Twenty-three patients under 40 years of age (mean, 28.0 years) with thoracolumbar or lumbar spine fractures underwent posterior stabilization without fusion. Implants were removed at a mean of 9.75 months (range: 6–17 months) after initial fracture fixation, and patients were observed for >18 months. Changes in the sagittal alignment of operatively fixed segments and the heights of vertebral bodies as well as the restoration of segmental motion (flexion–extension and right–left bending views) were measured. Clinical aspects, such as gross deformities and functional abilities, were also investigated. Heights of fractured bodies were well maintained at the final follow-up. Preoperative mean sagittal angle was 17.2° kyphosis, which improved to 2.8° lordosis after fracture fixation. Just before implant removal, the sagittal angle was 1.7° kyphosis, then 2.4° kyphosis immediately after implant removal, and 5.9° kyphosis at the final follow-up. Mean segmental motion was 14.2° in the sagittal plane and 13.1° in the coronal plane at the final follow-up. Most patients were satisfied with final gross appearance and functional outcome. The described nonfusion method seems to be effective in achieving favorable sagittal alignment and regaining motions of fixed segments. The present study suggests that the nonfusion method may be an effective option for managing thoracolumbar fractures, especially in young active people.⁴¹

SUMMARY

The goals of thoracolumbar injury treatment are to maintain spinal alignment and stability, preserve neurologic function, and minimize complications. We have gained an improved understanding of these injuries through evolving classification systems and imaging modalities. Early and accurate assessment of thoracolumbar injuries results in better management.

Advances in imaging capabilities as well as a more thorough evaluation of injury morphology, neurologic status, and PLC integrity have led to an improved decision-making process. When indicated, surgical treatment strategies (approach and construct) are based upon the pathomechanics of the injury. Ensuring fracture stability, whether operative or nonoperative, improves outcomes and patient satisfaction, and allows for earlier mobility.

KEY POINTS

- Thoracolumbar fracture treatment has evolved with improved injury description and classification.
- Early recognition of thoracolumbar injuries allows for accurate assessment of spinal stability and neurologic deficits.
- Treatment strategies remain controversial, but a new scoring system (TLICSS) improves the decision-making process on appropriate intervention.
- The principles of operative treatment include restoration of spinal alignment and stability, prevention of neurologic deterioration, and early mobilization of the patient.
- The incidence of vertebral osteoporotic compression fractures will continue to rise as our population ages, requiring constant vigilance regarding treatment strategies.

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Thoracolumbar Trauma: Lower Lumbar Fractures

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Snapshot

- » Epidemiology, Biomechanical and Anatomical Aspects of Lower Lumbar Spine Fractures
- » Literature Review
- » Conservative Treatment
- » Surgical Indications
- » Surgical Techniques
- » Postoperative Care
- » Prognosis

■ EPIDEMIOLOGY, BIOMECHANICAL AND ANATOMICAL ASPECTS OF LOWER LUMBAR SPINE FRACTURES

The annual incidence of spinal fractures is approximately 64 per 100,000 in the United States.¹ Common causes of spinal injuries are motor vehicle accidents (50%), falls from height (21%), violence injuries (11%), sports injuries (10%), and other reasons (8%). Due to anatomical and biomechanical characteristics of the thoracolumbar spine, the majority of thoracolumbar injuries are located between T10 and L2.² Lower lumbar injuries between L3 and L5 only account for a small percentage of thoracolumbar fractures (approximately 14%).^{3,4} Anatomically and biomechanically, the region of L3–L5 differs from other thoracolumbar areas. The L5 and sometimes the L4 vertebrae are stabilized by iliolumbar ligaments. The pelvis acts as an additional stabilizer against traumatic forces.⁵ The physiological lordosis of the region with the apex normally located at L3 leads to a load distribution that differs from other thoracolumbar areas. In contrast to the thoracolumbar junction, axial forces run through the posterior aspect of the vertebral bodies. Hence, traumatic axial compression forces produce uniform compression of the vertebral body not typically resulting in a kyphotic deformity.⁶ However, if a posttraumatic kyphosis occurs, it is difficult to compensate

and may lead to a global imbalance. It has been shown that restoration of the sagittal lumbar lordosis (L1–S1) to angles $>25^\circ$ is associated with an improved functional outcome after correction of painful posttraumatic kyphosis.⁷

Concerning possible neurological deficits in the lower lumbar spine, the following aspects have to be considered: The widest diameter of the spinal canal can be found in the lumbar region. There have been several reports of traumatic canal narrowing of as much as 90% in the cross-sectional area without a neurological deficit especially at L4–L5. The conus medullaris typically ends between L1 and L2 and the cauda equina behaves similar to peripheral nerves in terms of functional recovery.⁸ Possible risk factors for neurological deficits in the lower lumbar spine are the combination of severe spinal stenosis and disruption of the posterior ligamentous complex.⁹ The anatomical characteristics mentioned may help to explain the infrequency of severe neurological deficits and the potential neurological recovery when such a fracture is present.¹⁰

■ LITERATURE REVIEW

Looking at the literature there are limited studies about the treatment of lower lumbar vertebral fractures. Outcomes of conservative and surgical treatments were presented at these studies, but none of them has large series. Although

isolated L5 fractures are rare, many of these studies include cases only with L5 fractures. In conclusion, the level of evidence regarding the treatment of lower lumbar fractures is fairly low.

Chan et al. performed a retrospective view of 20 conservatively treated patients.¹¹ Patients suffered from lower lumbar burst fractures (L2–L5). None of the patients had neurological deficit at the time of injury. Total follow-up averaged 3.9 years. Average of kyphotic deformity increased meanwhile, but insignificantly, 90% of patients had a good to excellent outcome, 10% had fair outcome, 75% of the patients reported mild to moderate pain, but none of them was physically restricted due to pain. The authors concluded that conservative treatment should be the treatment of choice for lower lumbar fractures in patients without neurological deficits.

Lehman et al. operated 32 patients with lumbar burst fractures.¹² All of the patients were in military service and all suffered from combat-related spinal injuries. Nineteen of the included patients had lower lumbar burst fractures (L3–L5). Interestingly, patients who carried armors mostly had lower lumbar fractures. Though carrying armors lower the force in thoracolumbar junction, it transfers the force to lower segments. More than half of the patients had neurological deficits. Twenty-two of the patients underwent surgery. Postoperatively, neurological deficits remained in all but one patient. The authors recommended surgical treatment for high-energy lower lumbar spinal traumas.

Ramieri et al. reviewed retrospectively 19 patients with L5 burst fractures.¹³ Six patients had motor deficits and 12 patients had sphincter dysfunction. They performed posterior stabilization in 18 patients and a combined posterior–anterior stabilization in one patient. Pain relief was significant in most of the patients. Some of the patients recovered neurologically. Like most of the other spinal surgeons, the authors found anterior stabilization to be a difficult procedure. They suggested posterior stabilization in cauda equina syndrome and nerve root injuries. The authors also pointed out that posterior approach is sufficient for stabilization, decompression and restoring the sagittal profile of the spinal column for L5 burst fractures.

Sebesta et al. followed 11 patients with L5 burst fractures treated by posterior instrumented spinal fusion.¹⁴ Average follow-up was 18 months. They observed loss of vertebral height and loss of reduction with the development of a consecutive local kyphosis. Three patients had loss of lordosis by average of 9° because of broken screws. At the end of the study, all but one patient had pain and

neurological disorders. The authors concluded that good clinical outcomes were in contrast with radiological findings. They suggested that posterior stabilization is sufficient enough for treatment of L5 burst fractures.

In 2007, Butler et al. presented a study with 10-year follow-up of 14 cases with L5 burst fractures.¹⁵ They compared the results of conservative and surgical treatment. None of the patients had neurological deficits. Ten patients were treated conservatively and four patients underwent surgery. The authors reported better radiological outcome in the surgically treated group. In conservative group, loss of height and kyphotic deformity were more frequent. The authors advised for conservative treatment for patients with L5 burst fracture, who do not suffer from neurological deficit, major fragments in spinal canal, or severe bony deformity, respectively.

Studies comparing outcomes of surgical and conservative treatment are limited in the literature. In 1992, An et al. studied retrospectively 20 patients with lower lumbar burst fractures.¹⁶ Seven patients were treated conservatively and 13 patients underwent surgery. Both groups included patients with neurological deficits, but after treatment none of the deficits persisted. In the conservative group, there was 31% loss of vertebral height on average, but only 19% in the operated group. Furthermore, the resulting kyphosis of 9.2° on average was significantly higher in the conservative group. The authors suggested that in spite of radiological findings, conservative treatment should be chosen in neurologically intact patients with lower lumbar fractures. If case of surgery, they recommended short rigid fixation.

Another comparative study was published by Seybold et al.⁵ They retrospectively reviewed 42 patients that is one of the largest published series of lower lumbar burst fractures. Patients were treated between 1980 and 1996. Average follow-up time was 45.2 months. Twenty patients were treated conservatively and 22 patients surgically. Both groups consist of both neurologically intact and injured patients. At the end of the study, the authors showed that final functional status was similar in both groups. Looking individually at the level L3, L4 and L5, the authors could not find any significant difference in the long-term clinical results. In contrast, patients undergoing conservative treatment for L3 fractures developed greater loss of height and local kyphosis. Nevertheless, functional outcome in the conservative group was satisfying, so that the authors suggested conservative treatment as a viable treatment option.

CONSERVATIVE TREATMENT

It is a common standpoint that conservative treatment can be chosen in stable fractures with posterior ligamentous continuity and without neurological deficits.^{5,11,13,15-18} In doubt, MRI scan should be performed to rule out any injury of the posterior ligament complex that can be overseen easily.¹⁹ No consensus exists regarding the specific type of conservative treatment. Typically, treatment consists of pain medication, initial bed rest followed by mobilization with cast or brace. The authors recommend bracing with a rigid orthosis (e.g. Boston-Overlap-Brace) for 6–12 weeks, depending on the type of fracture. Patients should be followed closely and standing X-rays should be obtained after 1, 4, 12, 24, and 48 weeks, respectively. Increasing kyphotic or scoliotic deformity, together with ongoing pain are reasons to reconsider surgical therapy. Accompanying physiotherapy with strengthening of both, abdominal and lumbar muscles should be conducted. Occupational therapy is recommendable, especially in elderly patients.

SURGICAL INDICATIONS

The purposes of the surgical treatment are to remove any mechanical pressure from neural structures, to correct kyphotic deformity, to achieve anatomical reduction, and, most important, to obtain a stable and functional spine.

From the authors' point of view, any neurological deficit indicates surgical treatment, especially in unstable situations. In contrast to other regions of the thoracolumbar spine, neurological deficits may not only be due to the traumatic impact but also due to the persistent compression of the cauda equina or nerve roots, respectively. The decompression of the entrapped neurological structures may therefore reduce (radicular) pain and promote neurological recovery. However, we admit that currently no evidence exists regarding the effectiveness of surgical decompression. This fact has to be discussed with the patient before performing surgery.

Highly unstable fractures (B- and C-type injuries according to AO-Magerl³) are indications for surgical stabilization, too. This includes flexion-distraction injuries and fractures with dislocation. Special considerations that may stress surgical treatment are concomitant polytrauma, ankylosed spine, obesity, and osteoporosis, respectively.

There is an ongoing discussion about the treatment of burst fractures as described above. While incomplete

burst fractures (type A3.1 according to AO-Magerl³) can be treated conservatively in the majority of cases, burst split or complete burst fractures (types A3.2 and A3.3 according to Magerl³) can cause local kyphosis and unbearable pain. Therefore, the latter types can be treated surgically in selected cases.

SURGICAL TECHNIQUES

Surgical therapy involves stabilization of damaged motion segments and decompression of neural elements, if necessary. In case of greenstick fractures of the anterior cortex of the lamina or increased interpedicular distance, dural tears should be suspected. In such cases, any reduction maneuvers may entrap neurological structures. Therefore, decompression and exploration of the dural sac should be performed beforehand.²⁰ Posterior decompression can easily be performed by laminectomy and stabilization can be achieved with transpedicular screw fixation.^{17,21}

Stabilization can be done posteriorly, anteriorly, or combined. Posterior or/and anterior stabilization are options for the surgical treatment of thoracolumbar fractures, but in lower lumbar fractures anterior stabilization may be difficult because of the major vessels.^{13,22} Corpectomy, lateral plating, and vertebral body replacement with cage can be performed with anterior or lateral retroperitoneal approaches. Anterior column support is even possible from posterior via transpedicular bone grafting or cage implantation.^{17,23}

In cases of severe vertebral body comminution with marked kyphosis and persisting fragments in the spinal canal, a combined anteroposterior approach provides optimal stabilization and decompression while it reassures lumbar lordosis.¹⁰

Obviously, more aggressive surgery may inevitably lead to higher complication rates. The pros and cons have to be balanced and explained to the patients before performing surgery.

The majority of authors favor posterior surgery with short transpedicular constructs.^{5,13,14-16}

However, the treatment of choice may depend on regional characteristics and treatment recommendations. In a German multicenter study including 111 patients with lower lumbar fractures, 93% of patients underwent surgery, 57% were stabilized only from posterior, 41% underwent combined anterior-posterior stabilization and 2% were stabilized only from anterior, respectively.²⁴

Posterior Stabilization

In the lower lumbar spine, posterior stabilization should aim to save segments and mobility and therefore be as short as possible. Today, posterior stabilization is typically performed with internal fixators including pedicle screws.²⁵ Because of the high loads in the lower lumbar spine, the authors recommend the use of screws with 6-mm diameter whenever possible.²⁶ Furthermore, 6-mm titanium rods or 5.5-mm cobalt-chrome rods should be used to avoid rod failure. As one of the defined surgical goals is anatomical reduction, angular-stable internal fixators with monoaxial screw systems are advisable. Polyaxial screw systems are inferior concerning stability that have shown higher loss of correction in the postoperative course.^{27,28} Using the above-mentioned monoaxial angular-stable constructs, short fixation typically involving only two segments is possible in the vast majority of cases. Additional short pedicle screw insertion at the effected level can enhance the overall stability.²⁷

Recently, percutaneous stabilization has become popular in some geographical regions. Percutaneous stabilization leads to less soft tissue damage, but fusion is technically not possible.²⁹ Thus, percutaneous stabilization might be an alternative to brace treatment. Loss of reduction especially after implant removal is a typical risk of this treatment concept. However, in elderly patients with osteoporosis the authors recommend percutaneous polymethyl-metacrylate (PMMA)-augmented pedicle screw stabilization with or without additional kyphoplasty of the affected vertebral body.³⁰ In our experience, at least good short-term result can be expected with the percutaneous techniques (Figs. 86.1A to F).

Combined Stabilization

Combined anterior-posterior stabilization may be indicated in cases with severe destruction of the vertebral body or insufficient spinal canal clearance after posterior decompression.³¹ In comparison to isolated posterior stabilization, additional anterior stabilization improves biomechanical stability and leads to less loss of correction in the postoperative course.^{32,33} Since bone harvesting from the iliac crest carries a significant risk of morbidity, we recommend the use of titanium mesh cages or expandable titanium cages. Care should be taken to adjust the angulation of the endplates according to the local degree of lordosis (Figs. 86.2A to E). Otherwise, implant subsidence may occur. The additional use of an anterior plate can

further increase the stability and enhance bony fusion, but does neither affect cages subsidence, nor clinical outcome.³⁴

Today, minimally invasive anterior approaches are technically feasible, safe, and effective.³⁵ The anterior retroperitoneal approach to the lower lumbar spine can either be performed from the front or from the side. From the authors' experience, L4 and L5 should be addressed via an anterior (pararectal) retroperitoneal approach. At the levels L4 and L5, the main vessels have to be mobilized before proper corpectomy and fusion can be performed (Fig. 86.2C). At the level L3, both anterior and lateral retroperitoneal approaches are possible. In patients with bulky psoas muscles, the lateral approach carries the risk of damaging the lumbar plexus.

Complications

With an overall complication rate of approximately 9% in large series, surgery for thoracolumbar trauma has shown to be relatively safe.³³ Typical complications are infections, loss of correction, and implant failure, respectively. The rate of reported revision surgery due to complications is 2.8%.³³ Available studies concerning the surgical treatment of lower lumbar spinal fractures only include low numbers of patients. Therefore, limited information concerning complications can be obtained from them. Implant failure, especially in posterior surgery without anterior support, reflects the typical complication in up to 27%.¹⁴ Infections are reported in up to 18%.^{12,14} Typical reasons for revision surgery were hardware complications or progressive kyphosis.⁵

The anterior minimally invasive access carries an overall complication rate of 12.5%. Typical complications are dural tears (2.5%), intercostal neuralgia (2.5%), deep vein thrombosis (2.5%), pleural effusion (1.3%), wound infection (1.3%), hardware failure (1.3%), and hemothorax (1.3%), respectively.³⁶

POSTOPERATIVE CARE

Postoperative rehabilitation should start immediately after surgery. Patients can be mobilized without a brace but should not lift heavy weights for up to 3 months. Standing X-rays should be obtained after 1, 4, 12, and 48 weeks, respectively. Accompanying physiotherapy can reduce postoperative discomfort and ease occupational rehabilitation. Strengthening of both, abdominal and lumbar muscles, should be conducted. Occupational therapy is recommendable, especially in elderly patients.

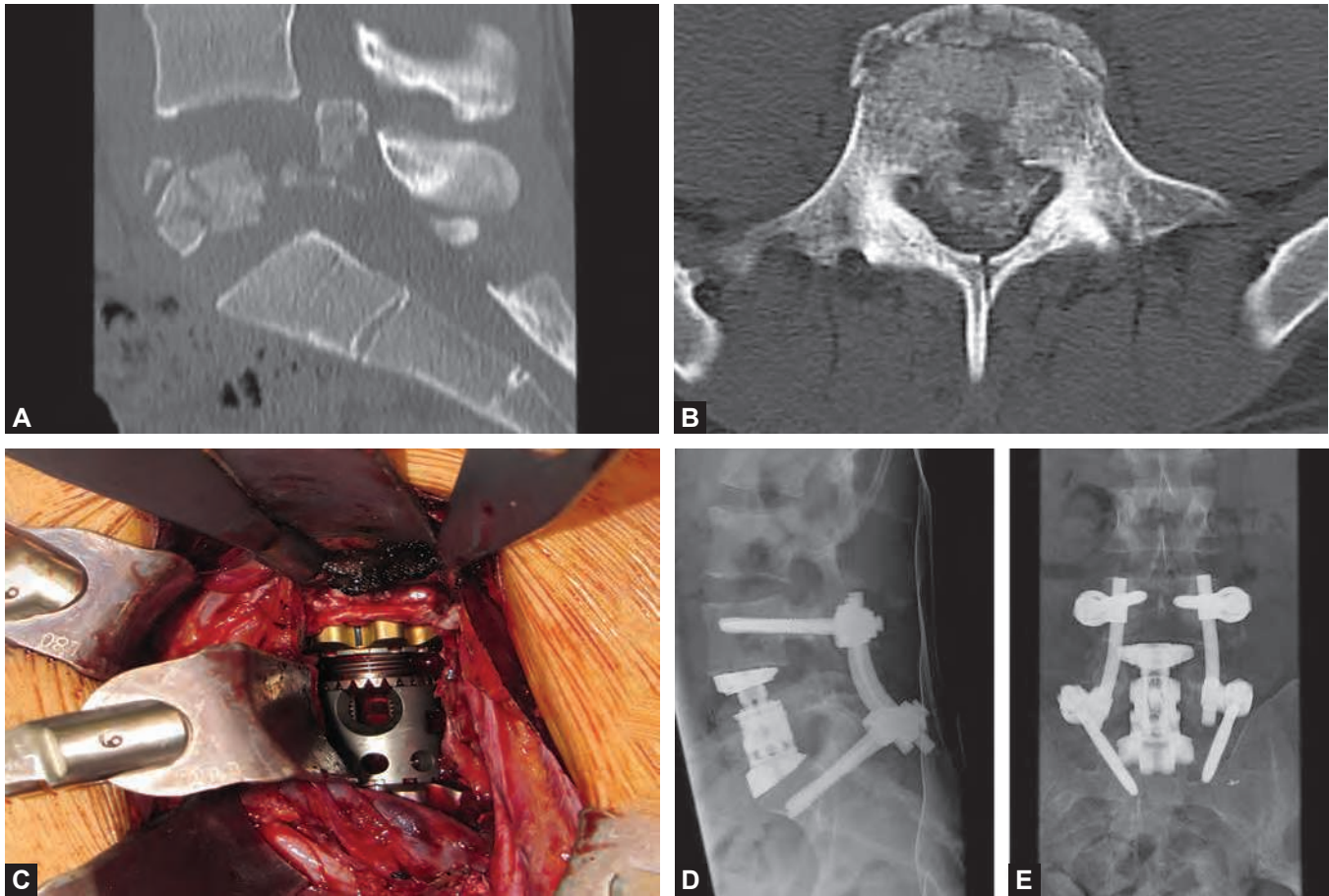


Figs. 86.1A to F: A 69-year-old male patient with osteoporosis (T-score -3.64) and increasing pain after he collapsed 5 months ago. On admission, heavy back pain (VAS 9) and neurogenic claudication. Complete burst fracture of L3 (A3.3 AO-Magerl). Conservative treatment attempt failed. Posterior percutaneous PMMA-augmented stabilization from L2 to L4 and minimally invasive interlaminar spinal decompression at L3/4. At 6-month follow-up, moderate back pain (VAS 3) and unlimited walking distance.

PROGNOSIS

Good to excellent outcome can be expected in 66–90% of patients, regardless of the type of treatment.^{5,11} However,

only one-third of patients report no pain at all after 2 years, and only 14% report unrestricted back function.³³ The return to work rate is between 64% and 100% depending on the neurological status.^{5,11,16} Conservative treatment



Figs. 86.2A to E: A 22-year-old polytraumatized male patient with complete burst fracture of L5 (A3.3 AO-Magerl) and neurological deficit (ASIA B). Immediate posterior bisegmental stabilization and fusion (L4–S1) including laminectomy of L5. Staged anterior minimally invasive retroperitoneal corpectomy L5 and vertebral body replacement with expandable cage. Six-month follow-up with improvement in neurological deficit (ASIA C).

seems to carry no risk for neurological deterioration, regardless of the type of fractures.^{5,10-12} However, improvement in neurological deficits after surgery is reported in 42–87%.^{5,13} Anterior decompression may improve neurological deficits in selected cases, too.¹⁰ Surgery leads to significantly better radiological results regarding the final kyphotic deformity and the loss of vertebral height.^{5,10,16,33} But no study could prove any correlation between radiological and clinical outcome so far. About half of the patients reported localized pain after posterior stabilization and 42% reported localized pain after anterior stabilization.³³

KEY POINTS

- Lower lumbar injuries between L3 and L5 only account for a small percentage of thoracolumbar fractures.

- Traumatic axial compression forces produce uniform compression of the vertebral body rather than kyphotic deformity.
- Conservative treatment (bracing) can be chosen in stable fractures with posterior ligamentous continuity.
- Neurological deficits and highly unstable fractures are indications for surgical stabilization.
- Short posterior stabilization with transpedicular screws is sufficient in the vast majority of cases.
- The majority of patients will achieve good to excellent outcome but residual back pain is common.

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Surgical Treatment for Sacral Fractures

Kota Watanabe, Chambliss Harrod

Snapshot

- » Epidemiology
- » Anatomy
- » Assessment of Sacral Fracture
- » Radiographical Evaluation
- » Classification
- » Sacral Insufficiency Fractures
- » Nonoperative Treatment
- » Surgical Treatment
- » Treatment of Unstable Pelvic Ring Injury
- » Treatment of Spinopelvic Instability
- » Fixation Technique
- » Decompression Surgery

INTRODUCTION

Optimal management of sacral fractures is multifactorial with emphasis on fracture classification or morphology, neurologic status, general medical condition, and local soft tissue environment (skin). Given the relative paucity of sacral fractures and complex management, the literature and subsequent treatment recommendations are primarily based on retrospective studies. Surgical treatment goals for unstable sacral fractures include reduction and stabilization of pelvic ring and/or spinopelvic integrity while preventing deterioration of neurologic deficits, and allowing early mobilization, rehabilitation, and recovery.

EPIDEMIOLOGY

Sacral fractures are typically high-energy traumatic injuries, which have classically been characterized as pelvic more than spinal fractures [anteroposterior compression (APC), lateral compression (LC), vertical shear, or combined pelvic mechanisms]. About 57% sacral fractures result from motor vehicle crashes, 18% from motor vehicles striking pedestrians, 9% from motorcycle accidents, 9% from falls from a height, and 4% from crush injuries.^{1,2} Sacral fractures occur in 10–45% of all pelvic fractures^{1,3–7}

and <2–5% of sacral fractures occur as isolated injuries.^{1,8,9} The latter typically results from a direct blow or fall onto the sacrum. Among types of sacral fractures, 5–16% are transverse and carry a high frequency of neurologic injury.^{5,6}

ANATOMY

The sacrum serves as the anchor of the pelvic ring attaching to bilateral pelvic arches (ilium, ischium, and pubis) via stout anterior and posterior sacroiliac ligaments. It also connects the mobile lumbar spine to the pelvic ring. Sacral injuries understandably cause not only pelvic ring but also spinopelvic instability, which may result in severe neurologic deficits.^{10–13} Neurologic injuries caused by sacral fractures range from incomplete mono radiculopathies (root palsies) to complete cauda equine syndrome. Additionally, ventral rami of the S2 through S5 roots contribute to the prevertebral and presacral parasympathetic plexus and nerves that regulate sexual function, bladder, and rectal function. Surgical anatomy mandates understanding the location of the L5 nerve roots that lie on the anterosuperior surface of the S1 vertebral body and ala. These roots are susceptible to a neurapraxis stretch injury during open book APC pelvic injuries. They are also the most likely root to be injured with inadvertent placement of sacroiliac

screw fixation. Lastly, the posterior rami of the sacral roots consist of small sensory fibers, with contributions to the cluneal nerves, which are susceptible to injury during harvesting of posterior iliac bone graft procedures.

ASSESSMENT OF SACRAL FRACTURE

Sacral fractures are often associated with other concomitant high-energy injuries. Multiply-injured polytrauma patients are often obtunded, comatose with up to 20% of these patients either unconscious or intubated prior to appropriate orthopedic or neurologic consultations.¹⁴ Hence, proper complete history, physical and neurologic examinations are difficult. Standard advanced trauma life support principles are mandatory as sacral fractures are frequently overlooked at initial presentation in 24–70% of cases.¹⁵

- When pelvic or sacral fractures are suspected, identification of the following must occur: Presence of life-

threatening hemorrhage from iliac vessels, anterior perisacral venous plexus, or superior gluteal artery. These are often associated with APC (open book pelvic fractures) type injuries that require emergent volume reduction in the pelvic ring with a sheet around the trochanters, pneumatic compression devices, or, rarely, pelvic clamps until placement of an anterior pelvic external fixator can be applied (Figs. 87.1A to C). Volume replacement and subsequent arterial embolization must be arranged concomitantly.

- Presence of extensive lumbosacral fascial degloving injury (Morel-Lavallee syndrome) that substantially affects strategy of surgical treatment.
- Presence of concomitant thoracolumbar fractures.
- Presence of neurologic injury. Neurologic examination includes motor and sensory function, reflexes, and elicitation of reflexes including the perianal wink, the bulbocavernosus, and the cremasteric reflexes are



Figs. 87.1A to C: Anteroposterior pelvic radiograph (A) demonstrating anterior widening between the two pubic arches. The patient had an unstable anteroposterior compression injury with the anterior pubic rami splaying and posterior sacral widening with horizontal instability (B) that required immediate anterior external fixator placement and subsequent posterior open reduction and tension-band plating of the sacral fracture (C).

recommended. Light touch and pinprick sensation along the perianal concentric dermatomes of S2 through S5.

- Presence of pelvic ring and spinopelvic instability.
- Presence of injuries to the genitourinary system (urethral, bladder) secondary to displaced fracture fragment.

RADIOGRAPHICAL EVALUATION

Two-view radiographic evaluation using only a standard anteroposterior (AP) and cross-table lateral X-rays of the pelvis often do not adequately diagnose sacral fractures. Pelvic inlet and outlet radiographs are recommended to improve visualization of the sacrum. Associated signs of sacral fractures on plain X-rays are L4 or L5 transverse process fractures, anterior pelvic ring disruptions, and a “stepladder” sign.¹⁶

Computed tomography (CT) is recommended for diagnosis and determines fracture type. Additionally, sagittal and coronal reconstruction images with or without 3D reconstructions should be obtained for better visualization of the fracture and are essential to best categorize the fractures.

Magnetic resonance imaging (MRI) is not only superior in evaluating the neurologic and soft tissue (ligamentous) structures but also significantly helps in determining sacral stress fractures, insufficiency fractures.

CLASSIFICATION

Sacral fractures were often included into the classification of pelvic ring fractures including the Letournel, Tile, and AO-ASIF classification systems that identify the force imparted on the pelvis as well as the resultant instability (vertical or horizontal). Several additional “spine based” classifications have been developed for sacral fractures.

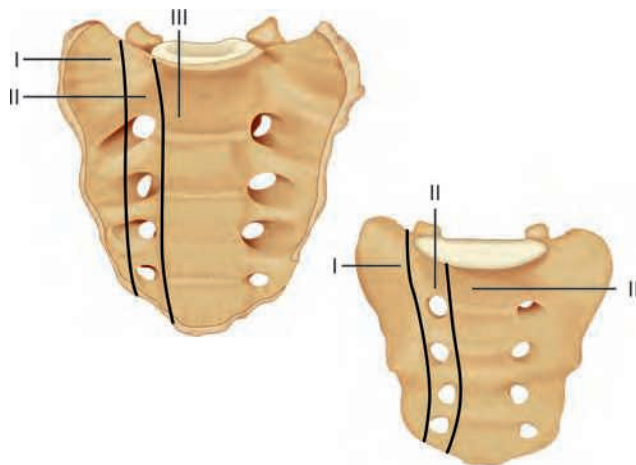
Denis Classification¹

Denis classification system of sacral fractures divides the sacrum into three zones in relation with the position of neural foramina and spinal canal.

Zone I: Fracture line is lateral to the neural foramina. It is the most common pattern (50% of the fractures in the series of Denis et al.), which resulted in sciatic nerve or L5 nerve root injury in 5.9% of cases.

Zone II: Fracture line is through foramina. It is the second most common pattern (34% of the fractures in the series),

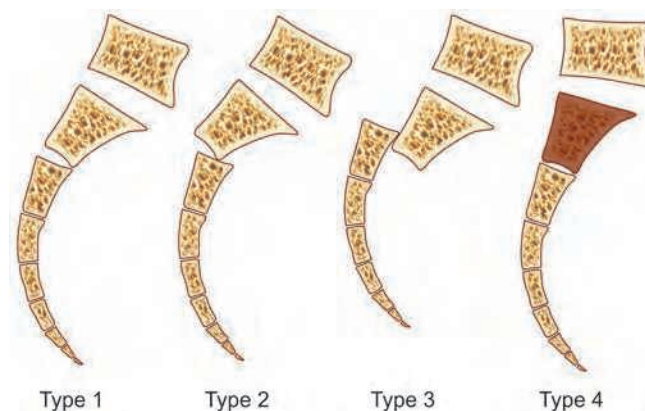
which resulted in L5, S1, or S2 injury in 28.4% of cases. Zone II fractures with a shear component have increased risk of neurologic deficits.



Zone III: Fracture lines involve the spinal canal. It is the least frequently encountered fracture pattern (16% of the fractures in the series). Neurologic deficit occurred in 56.7% of patients. Transverse fractures involving the S1-S3 segments tend to have a higher prevalence of bladder dysfunction than those at S4 and below. Among neurologic injuries, bowel and bladder control or sexual function was impaired in 76% patients. Since bilateral zone I or II injuries are extremely rare, closer inspection for zone III injury and an obscure transverse fracture line should be performed using CT coronal images.

Subclassification of Denis Zone III Fracture

The transverse fracture in Denis zone III was further classified in to three types by Roy-Camille.¹⁷



Type 1: Simple flexion deformity of the sacrum with minimal to no translation.

Type 2: Incomplete anterior sacral translation with kyphosis.

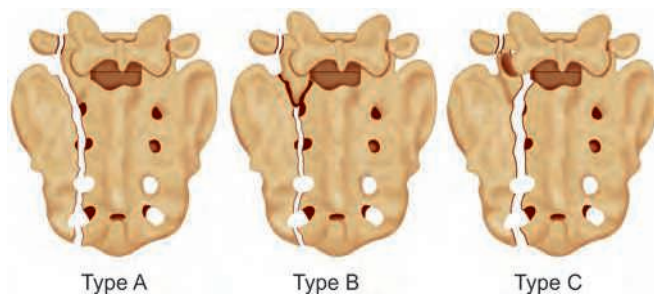
Type 3: Complete translation with complete sacral displacement.

Strange-Vognsen and Lebech further modified Denis zone III fracture by adding type 4.¹⁸

Type 4: Segmental comminution of the S1 vertebral body caused by axial loading.

Isler System¹⁹

Isler system classify sacral fracture based on the location of the major vertical fracture line relative to L5-S1 facet, which predicts the potential of lumbosacral subluxation or complete lumbopelvic dissociation.



Type A: Fracture through the sacrum and located lateral to L5/S1 facet. This type of fracture will not cause lumbosacral instability, but may have some negative impact on pelvic ring stability.

Type B: Fracture through the sacrum and run through the L5-S1 facet. The fracture can be differentiated as extra-articular fractures of the lumbosacral junction and articular dislocation with displacement of the facet.

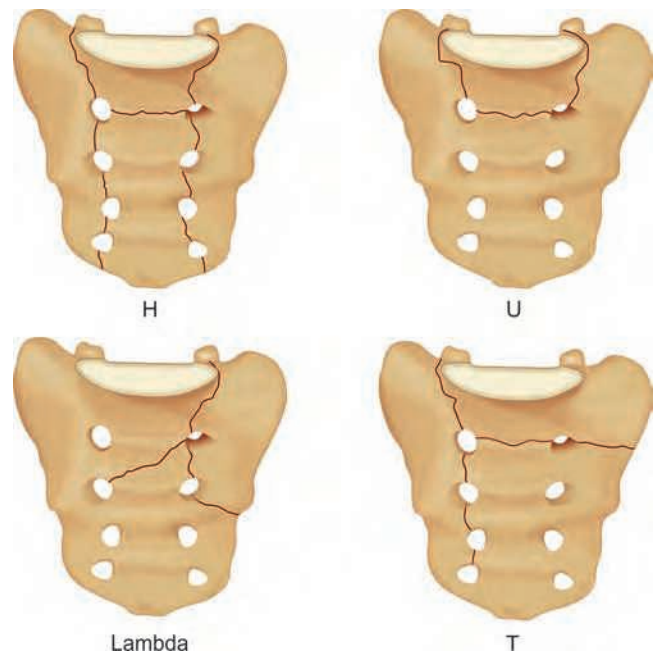
Type C: Fractures through medial to the facet crossing into the neural arch. These fractures may lead to significant instability and can lead to lumbosacral dissociation when occurred bilaterally.

Descriptive Classification

U-shaped fracture is first described by Roy-Camille in 1985.¹⁷ Additional morphologic variations in this fracture pattern have been described as “H,” “T,” and “lambda” patterns when associated with other pelvic ring disruptions.

U-shaped fractures were further classified into four types by sagittal displacements by subclassification of Denis zone III fracture.^{17,18} U-shaped sacral fractures usually result from a significant amount of axial load to the spine by which pivoting of the sacrum occur. The most common

mechanism of injury was suicidal jump,²⁰ followed by fall from height.²¹ These two injury patterns are responsible for the majority (67.2%) of all published cases. The horizontal fracture usually occurs between S1 and S2 and causes dissociation of the spinal column and the pelvic ring. The rostral part of the sacrum stays attached to the lumbar spine with the caudal part attached to the pelvic ring resulting in the aptly named spinopelvic dissociation. This type of fracture has a wide ranging potential of neurologic injuries from incomplete radiculopathy to complete cauda equina syndrome and ruptured nerve roots.^{1,6,9,22-24} Amongst patients with spinopelvic dissociations, neurologic injury was noted in 94.3%.²⁵



SACRAL INSUFFICIENCY FRACTURES

Sacral insufficiency fractures were first described by Lourie in 1982.²⁶ Sacral insufficiency fractures are estimated to occur in 1–5% of women aged above 55 years²⁷⁻²⁹ who are associated with postmenopausal osteoporosis.³⁰⁻³⁴ Insufficiency fractures are a subtype of stress fracture that results from normal stress applied to abnormal bone that has lost its elastic resistance. Sacral insufficiency fractures can occasionally be confused with metastatic disease, both clinically and on imaging studies.³⁵ The most common physical signs are low back or groin tenderness and restricted hip movement^{36,37} Neurologic deficit is rare. Usually, patients present with no history of trauma or a history of low-impact trauma.

The diagnosis of sacral insufficiency fracture is usually difficult by X-rays.³⁸ Bone scintigraphy and MRI are the most sensitive screening investigation. Magnetic resonance imaging can pick up signal from bone marrow edema that results from fracture inflammatory and reparation processes. T1-weighted images demonstrate a low signal intensity, while T2-weighted images demonstrate high signal intensity. T2-weighted short tau inversion recovery images and T2-weighted images with fat suppression are particularly sensitive to demonstrate fractures.³⁹

Bone scintigraphy with technetium-99 m medronate methylene diphosphonate is a sensitive technique for detecting sacral insufficiency fracture.^{32,37} A classic “H” pattern,⁴⁰ is considered to be diagnostic. However, the “H” pattern requires bilateral involvement and a horizontal fracture component to the sacral body that is not always present.

Conservative treatment is standard for treating sacral insufficiency fracture and consists of bed rest, restricted weight bearing, and analgesics for pain relief.^{37,41} Symptoms resolve in most patients by 12 months but can vary between 6 and 15 months.^{36,37,41,42} In fact, half of patients with pelvic insufficiency fractures will not return to their prior functional level, and there is a reported 14.3% overall mortality.⁴³ More recently, minimally invasive cement augmentation techniques similar to vertebroplasty have been advocated by interventionalists (sacroplasty) as an alternative to conservative therapy.⁴⁴⁻⁴⁸

■ NONOPERATIVE TREATMENT

Historically, indications for nonoperative management included nearly all sacral fracture patterns as implants were inadequate for reconstruction of these highly complex injury patterns. Contraindications to nonoperative care are an incomplete neurologic deficit with objective evidence of neural compression, and extensive disruption of the posterior lumbosacral ligaments. Nonoperative care consists of prolonged bed rest in skeletal traction, bed rest in a brace or cast with a unilateral or bilateral hip spica, brace immobilization (with a thoracolumbar spinal orthosis with a hip spica) with protected weight-bearing, or, ideally, early mobilization with protected weight-bearing. Typically, 2–4 months are required for healing a posterior pelvic ring fracture. Repeat imaging studies should be performed to verify that fracture healing is proceeding with satisfactory alignment (especially prior to anterior external fixator removal). Prolonged recumbency has increased risks of

thromboembolism, pulmonary complications, and skin breakdown. In terms of neurologic recovery, controversy still exists whether clinical results of surgical intervention are superior to conservative treatment.⁴⁹

■ SURGICAL TREATMENT

The goals of surgical treatment are anatomic reduction and stabilization of the fracture(s) with restoration of lumbosacral alignment in order to improve and/or prevent neurologic deficit, residual pain, and to enable early mobilization.^{50,51}

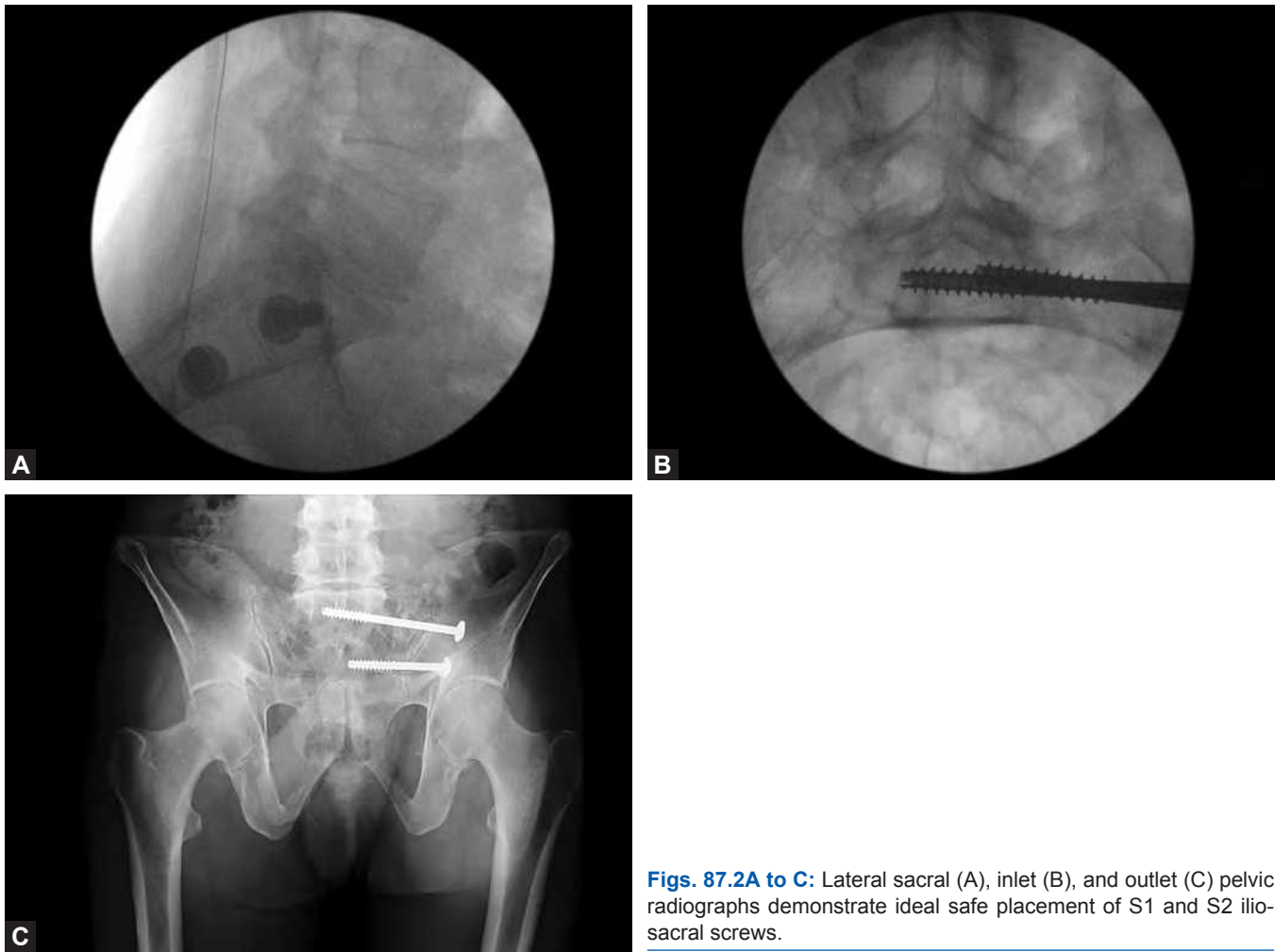
In patients with zone I and zone II fractures, surgical delays >5 days after injury were associated with less anatomic closed reductions.⁵² Delays >2 weeks in patients with neurologic compromise resulted in poorer outcomes.¹ Although surgical treatment should be considered as early as possible, the timing should be decided based on the purpose of treatment, the patient's general medical status, and the invasiveness of the intended surgical procedure. Early aggressive surgery in under-resuscitated patients can lead to undesirable surgical outcomes including excessive intraoperative blood loss, soft-tissue breakdown, and infection.

Sacral fracture surgical management options are best classified into treatment of unstable pelvic ring injuries and treatment of spinopelvic instability.

■ TREATMENT OF UNSTABLE PELVIC RING INJURY

For sacral fractures associated with substantial unstable pelvic injuries [APC II/III (anterior symphyseal widening >4cm), LCII/III fractures (horizontal instability associated with a combination of pubic/iliac/sacral fractures), and nondisplaced unilateral vertical shear fractures], the goal is to reduce pelvic volume to minimize additional blood loss by reduction in a displaced pelvic ring fracture including temporary skeletal traction, application of an anterior external fixator, placement of a pelvic clamp, or use of a wrap-around sheet. Additionally, radiologic intervention techniques such as angiographic embolization of bleeding vessels should be considered (*see Figs. 87.1A to C*).

During surgery, the anterior fixation should be considered prior to posterior lumbosacral procedure.² Usually, the anterior pelvic ring injury can be realigned and stabilized by anterior plate fixation, external fixation, or the use of retrograde pubic screws. This can partially stabilize the pelvic ring during a posterior procedure with prone posi-



Figs. 87.2A to C: Lateral sacral (A), inlet (B), and outlet (C) pelvic radiographs demonstrate ideal safe placement of S1 and S2 ilio-sacral screws.

tion and can enhance the reduction in the posterior part of the pelvic ring.

Denis type I fractures, nondisplaced vertical shear fractures, and other displaced, unstable (widened not compressed) sacral fractures not associated with neurologic impairment that do not appear to have closed down with anterior pelvic ring restoration with external fixator or anterior pelvic plating should be considered for posterior pelvic ring fixation. Use of traditional open reduction with posterior tension band plating techniques with fixation into bilateral posterior ilium is appropriate in patients who do not appear closed reduced completely pre- or intraoperatively (*see* Fig. 87.1C). However, percutaneous transiliac iliosacral screw fixation predominates now. Full bowel prep is helpful but not always mandatory, and avoidance of nitrous anesthesia is mandatory so bowel loops do not obstruct fluoroscopic guidance. It requires a combination

use of the lateral sacral view (to determine starting point and avoid the L5 root safely), inlet (to determine anteroposterior placement not in the canal), and outlet views (to avoid the neuroforamina) for safe screw placement.²⁰ A single 7.3 mm cannulated S1 screw, 2 S1 screws, or screws in S1 or S2 are possible depending on fixation needed (Figs. 87.2A to C). Fully threaded screws should be used in Denis II fractures to not further compress the neuroforamina and cause iatrogenic root injury. Partially threaded screws are indicated for sacroiliac joint widening or mildly displaced zone I fractures needing compression. Lastly, displaced anterior sacroiliac dislocations or fracture-dislocations in which the fracture lines do not exit posteriorly are best approached with an anterior ilioinguinal retroperitoneal approach to open reduce then placement of either a stout anterior sacroiliac plating that straddles the SI joint or posterior iliosacral fixation.

TREATMENT OF SPINOPELVIC INSTABILITY

While rare, spinopelvic instability can be a devastating lesion clinically and the lumbar spine dissociates from the sacropelvis typically via slipping into a position anterior to the sacrum. The lesion can occur with bilateral dislocations of the sacroiliac or L5-S1 facet joints, or trans-sacral fractures. Traumatic spinopelvic dissociations or U-shaped sacral fractures are characterized by a transverse sacral fracture in conjunction with bilateral sacral fracture-dislocations, resulting in mechanical dissociation of the upper sacrum and spine from the pelvis. The term of traumatic spinopelvic dissociation was proposed by Bents et al. to distinguish this injury pattern from lumbosacral fracture-dislocations or bilateral sacroiliac joint dislocations.^{10,13} For U-shaped fractures, spinopelvic fixation with L4 and/or L5 pedicle screws, iliac fixation (1 or 2 screws bilaterally), and screws (or triangular osteosynthesis) can provide optimum reconstruction and stability²⁵ (Figs. 87.3A to F). Iliosacral screw fixation as percutaneous osteosynthesis was performed in 31.7% of the U-shaped fractures in which the screws were either inserted unilaterally, bilaterally, or trans-sacally.²⁵ Failure to recognize the vertical instability associated with these fractures can often fail traditional pelvic reduction and fixation techniques alone (Figs. 87.4A to H).

FIXATION TECHNIQUE

Posterior stabilization techniques include percutaneous sacroiliac screw fixation, bilateral sacroiliac screw fixation

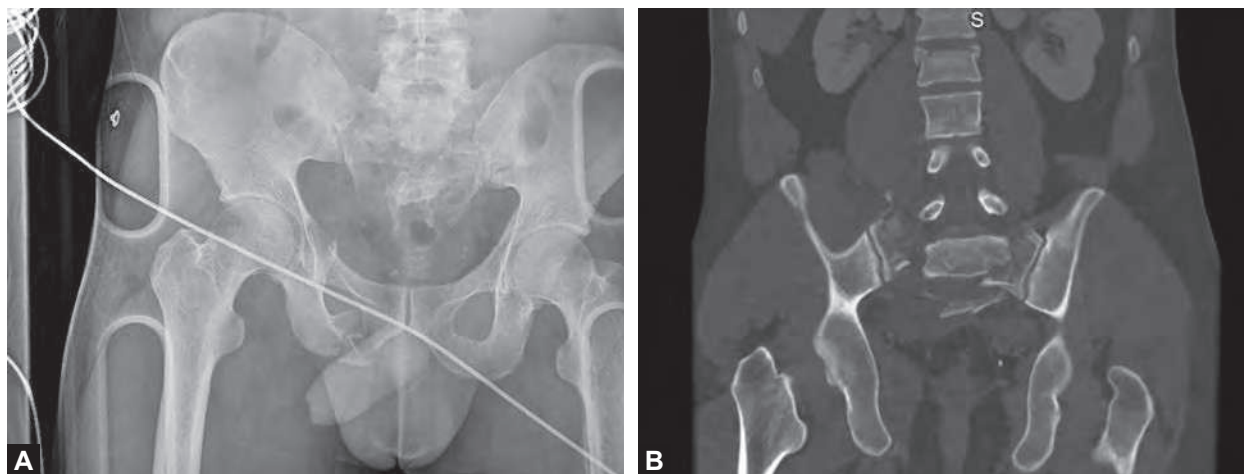
with posterior tension-band plate fixation, posterior alar plate fixation, and lumbopelvic segmental fixation. For decision making of the surgical strategy, skin condition including the presence of a Morel-Lavallee lesion can also be evaluated.

Triangular Osteosynthesis Technique

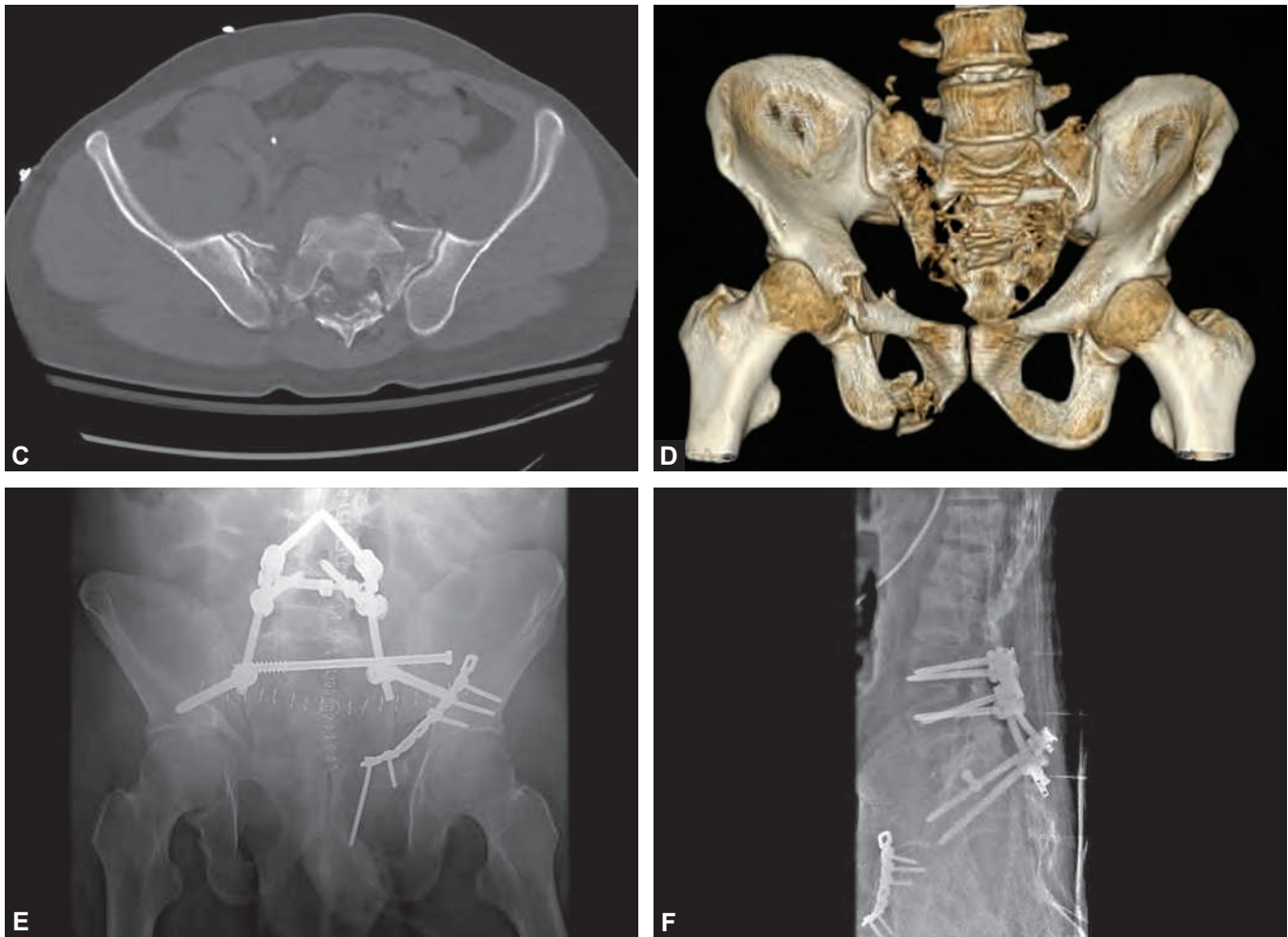
Triangular osteosynthesis technique combines the vertical component (lumbopelvic distraction osteosynthesis) with transverse fixation (iliosacral screw or transiliac/trans-sacral plate) that can allow early postoperative mobilization with full weight bearing.⁵³ In a cadaveric study comparing the biomechanical stability for vertical transforaminal fractures, the triangular osteosynthesis provides significantly greater stability than sacroiliac screws in vitro cyclical loading conditions.⁵³ In terms of complications, wound infections and pain due to prominent of spinal implants are comparatively common in patients with triangular osteosynthesis. In the systematic review, 3 out of 6 patients (50%) with triangular osteosynthesis and 2 out of 19 (10.5%) in the largest series of spinopelvic fixation needed removal of metalwork.^{11,12}

Lumbar Pedicle Screw and Iliac Screw

The construct consists of lumbar pedicle screws and iliac screws connected by longitudinal rods and transverse connectors to facilitate fracture reduction and stabilization. This construct also allows patient early ambulation without a brace. Complete decompression of neural tissues can be done using this construct.



Figs. 87.3A and B



Figs. 87.3C to F

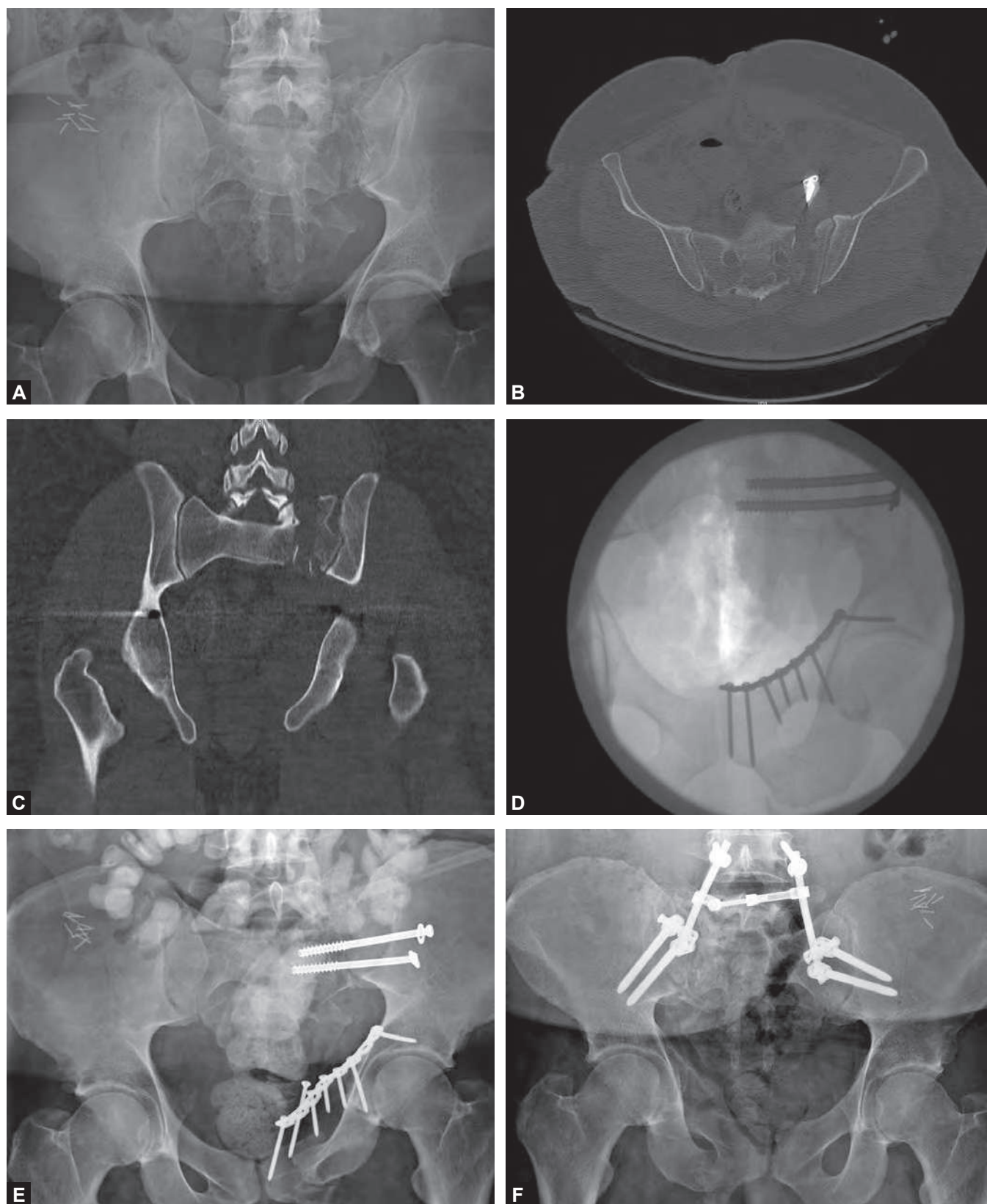
Figs. 87.3A to F: Initial trauma bay anteroposterior (AP) pelvis radiograph (A) demonstrating the H-type sacral fracture and right anterior pelvic ring fracture. Coronal (B) and axial (C) pelvic computed tomography images demonstrate the severe comminuted, unstable sacral fracture with three-dimensional coronal reconstruction (D). Postoperative AP pelvis (E) and lateral lumbosacral spine radiographs (F) demonstrate L4-S1 spinopelvic instrumentation (Synthes Pangea, West Chester, PA), right iliosacral screw fixation with a Synthes partially threaded 6.5 mm cannulated screw, and open reduction internal fixation (ORIF) R anterior pelvic ring fracture with a Synthes 3.5 mm pelvic reconstruction plate.

Sacroiliac Screw

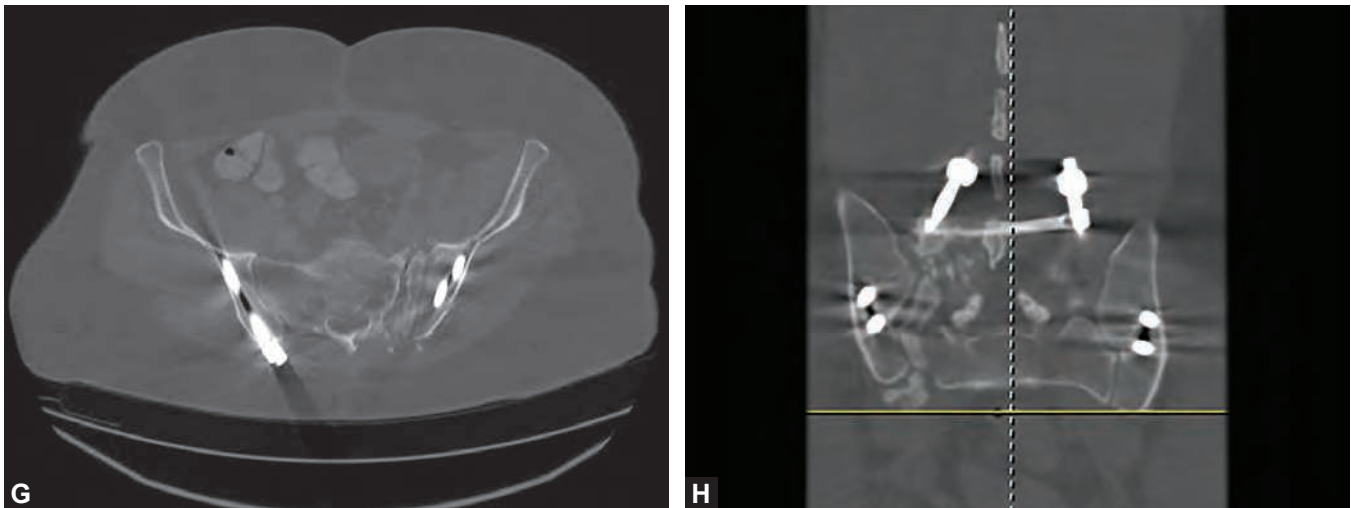
Sacroiliac screws, originally intended for sacroiliac joint injuries, are useful for treating vertical sacral fractures and sacral disruption.⁵⁴ The screws can be placed percutaneously under fluoroscopy with the patient in either the prone or supine position. Placement of screws is highly dependent on fluoroscopic imaging. The safety of these screws has been established in multiple clinical trials,^{28,55,56} and injury to neurovascular or gastrointestinal structures has been described as a rare complication. Potential indications for percutaneous placement of sacroiliac screws include a Denis zone I, II, or III sacral fracture, which can

be adequately reduced in a closed fashion. Denis zone III, Roy-Camille type 2, 3, or 4 injuries are less amenable to this form of fixation as a stand-alone device because of the inability to reduce these injuries by closed fashion. In zone II, fractures with segmental comminution are susceptible to overcompression and secondary foraminal entrapment when an iliosacral compression screw is used. Such injuries may be considered for fixation with two static sacroiliac screws or for iliolumbar segmental fixation.²

Nork et al.⁵⁵ reported successful results of percutaneous sacroiliac screw fixation in 13 patients with a Denis zone III, Roy-Camille subtype 1 or 2 fracture, and no substantial neurologic deficit. No deterioration of the sacral kyphosis



Figs. 87.4A to F



Figs. 87.4G and H

Figs. 87.4A to H: Anteroposterior pelvis radiograph (A) and computed tomography (CT) axial and coronal reconstruction images demonstrate severe left-sided pelvic fracture, combined vertical shear-LC [rotationally and vertically unstable Tile (B and C)] after initial fixation (D) and failure (E) of fixation with anterior ring open reduction internal fixation and closed reduction percutaneous posterior pelvic ring pinning. After removal of hardware, L4-Ilium spinopelvic fixation with intraoperative reduction was accomplished with posterior segmental instrumentation (Synthes Pangea, West Chester, PA) (F). Note the cranial screws require additional cross connectors, while the caudal screws hook directly to the rods. Postoperative CT (G and H) demonstrates screws in the ilium and supra sciatic notch column extending toward the anterior inferior iliac spine (AIIS).

angle was found despite the fact that the post-traumatic deformity was stabilized without aggressive attempts of reduction. The authors recommended insertion of bilateral midline-crossing sacroiliac screws when the technique is used to treat a zone III “H” or “U” fracture configuration.

DECOMPRESSION SURGERY

In the presence of satisfactory skeletal stabilization but persistent neuroforaminal or spinal canal compromise, a focal limited decompression may be performed with use of a limited midline exposure. From a neurophysiologic standpoint, decompression of compromised neural elements is preferably performed early, within the first 24–72 hours following injury, because of epineural fibrosis and increased scarring of the central canal and foramina. However, given an overall rate of neurologic improvement of approximately 80% regardless of treatment, the indications for and timing of surgical decompression in patients with neurologic injuries are somewhat controversial.^{6,57,58}

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Nonoperative and Operative Treatment of Sacroiliac Joint Dysfunction

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Snapshot

- » Anatomy
- » Biomechanics
- » Sacroiliac Joint Dysfunction
- » Physical Examination and Diagnostic Techniques
- » Imaging
- » Nonoperative Management
- » Operative Management
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INTRODUCTION

The sacroiliac joint (SIJ) is a highly specialized and heterogeneous synovial joint that connects the axial skeleton to the lower extremities, allowing the transfer and dissipation of forces between the two body regions. As a result, the joint has developed a unique bony anatomy with abundant ligamentous connections conferring this necessary stability. The minimal, but essential, physiologic motion that occurs in the SI is rarely a source of pain, but alterations to the joint as a result of trauma, pregnancy, or degenerative disease can result in abnormal motion and pain.

The SIJ along with its associated capsular and ligamentous structures are estimated to be the causative agent in approximately 15–20% of patients who present with axial low back and buttock pain.¹ The role of the SIJ in back pain has certainly undergone a great shift. At the turn of the 20th century, the SIJ was thought to be the principal cause of back pain and sciatica; however, the work of Mixter and Barr shifted focus to the herniated disc and with the advent of magnetic resonance imaging (MRI), the SIJ became an afterthought for most spine specialists, and perhaps an underappreciated cause of back pain. Nonetheless, the SIJ can be responsible for the symptoms in a subset of patients with low back and buttock pain as well as patients with persistent or new back pain after lumbar fusion, and a

thorough knowledge of the diagnosis and treatment of the dysfunctional SIJ can improve the care of these patients and avoid interventions aimed at treating discogenic or zygapophyseal joint pain in this population.

ANATOMY

The SIJ is a highly specialized diarthrodial synovial joint connecting the sacrum to the two ilia, critical for the transfer of loads between the spine and lower extremities. The sacrum is composed of five fused sacral vertebra, and the SIJ is typically formed between S1–S3 and the ilium.² The surface anatomy of the joint has been shown to be highly variable, but in general, the sacral portion is predominantly concave and the iliac portion is convex.³ This matching interdigitating anatomy provides inherent stability of the SIJ construct, as these surfaces have the highest coefficient of friction of any diarthrodial joint.^{4,5}

Further stability of the SIJ is provided by the multitude of primary and accessory SI ligaments that span the joint, including the ventral, dorsal, and interosseous ligaments. The anterior sacroiliac ligament is the thickened anterior capsule composed of dense connective tissue that extends between the ventral surfaces of the sacrum and ilium. The ventral SIJ capsule, as compared to other SIJ ligaments, is relatively thin, and Fortin et al. demonstrated the dispersion of contrast ventrally out of the SIJ in approximately

60% of patients undergoing intra-articular injections, indicating that these connections are not nearly as robust as their dorsal counterparts.⁶ In fact, only the anterior portion of the joint is truly synovial in nature and the dorsal aspect is composed of a network of interosseous SI ligaments.⁷ These interosseous ligaments have the largest volume of all the SIJ ligaments and in turn supply the greatest contribution to multidirectional stability.⁸ There are numerous dorsal accessory SIJ stabilizers, including the iliolumbar, sacrospinous, and sacrotuberous ligaments. Vrahas et al. later confirmed the importance of the interosseous and posterior ligaments and demonstrated the minimal role of the anterior SI ligaments on joint mobility.⁹

The joint surface of the SIJ is equally unique. The cartilage on the sacral side reaches a thickness of approximately 4 mm, while that on the ilium side does not exceed 1–2 mm at maturity, nearly three times thinner.^{7,10} Not only does the quantity of cartilage differ, but the quality of cartilage on the two sides of the joint is also quite different. Cartilage on the sacral side appears histologically similar to typical hyaline cartilage. Cartilage on the ilium side resembles fibrocartilage, and was only recently determined to be a more specialized variant of hyaline cartilage.¹¹

BIOMECHANICS

The primary function of the SIJ is to allow the transfer forces from the axial spine to the lower extremities providing the stability of the pelvic ring. In order to maintain the stability to facilitate its function, the joint is inherently immobile, allowing only minimal motion for dissipation of loads and facilitating parturition in females. Several studies have evaluated SI kinematics and essentially demonstrate limited but present motion in all three axes. Egund et al. looked at SI motion in asymptomatic volunteers in all planes and found that translation and rotation never exceeded 2 mm and 2°, respectively.¹² Vleeming et al. demonstrated similar findings, confirming that SIJ range of motion (ROM) rarely exceeded 2°. ^{13,14} The transfer of forces from the trunk to the ground is especially important with bipedal gait.¹⁵

A topic that is still unclear is the relationship between SIJ mobility and pain. Hypermobility has certainly been demonstrated as a cause of SIJ pain, particularly in patients with traumatic instability or multiparity.¹⁶ However, Stuesson et al. measured SIJ mobility in patients diagnosed with SIJ pain and found no significant differences

between symptomatic and asymptomatic patients, with maximal translation and rotation values of 1.6 mm and 3°, consistent with other kinematic studies.¹⁷ In summary, hypermobility can certainly be a source of SIJ pain; however, a painful joint is not necessarily, and perhaps rarely in the absence of trauma, hypermobile or unstable.

SACROILIAC JOINT DYSFUNCTION

Historically, SIJ dysfunction was at one point in the early 1900s thought by many surgeons to be the commonest cause of low back pain (LBP). When Mixter and Barr demonstrated radiating back and leg pain as a result of bulging and ruptured intervertebral discs in 1934 followed by the work of other authors including Ghormley lowering the rank of SIJ pathology in the differential diagnosis, the sacroiliac joint was nearly dismissed as a source of symptoms in LBP patients.^{18,19} Solenen et al. in 1957 re-explored this topic and identified a percentage of patients with pain originating from the SIJ while concluding that the SIJ was indeed a true articulation and a potential etiology of symptoms in patients presenting with LBP.²⁰

Several studies have demonstrated the presence of nerve fascicles containing myelinated and unmyelinated nerve fibers and various mechanoreceptors in the SIJ as well as in the respective periarticular tissues.^{21,22} The origin of these fibers is still subject to debate and may be variable among different patients as well as between different regions of the SIJ. Ultimately, most studies have demonstrated innervation from the lower lumbar and sacral nerve roots, predominantly from the dorsal rami of L4 through S1.^{23–25} Although the origin of the innervation has not been definitively shown, it is nonetheless clear that the SIJ and periarticular tissues are innervated and capable of producing pain in some proportion of patients.

Modern studies evaluating the prevalence of painful SIJ dysfunction are limited by the fact that there is no true single gold standard test to confirm the pain generator. Bernard and Kirkaldy-Willis examined the incidence of the SIJ as the etiology of symptoms in over 1,200 patients presenting with LBP and determined that the SIJ was responsible in 22.5% of patients, though these results were based almost solely on physical examination.²⁶ Other recent studies have acknowledged the limitations of physical exam and imaging alone, and utilized response to image-guided SIJ anesthetic injections as a confirmatory test. Schwarzer et al. evaluated 43 patients with LBP below

the lumbosacral junction and determined SIJ involvement by a combination of three factors: (1) response to intra-articular SIJ injection, (2) abnormalities on postarthrography CT scans and (3) concordant pain reproduction with distention testing. Seven patients in this study satisfied all three previously mentioned criteria, meaning that a conservative estimate of the prevalence of SIJ pain as the etiology of LBP symptoms would be 16%.¹ If significant relief with SIJ injection was used as the lone criteria, then prevalence of SIJ pain would be determined as 30% in this population. Although there is no true gold standard measure to confirm the SIJ as the etiology of symptoms, depending on inclusion criteria for LBP, the prevalence of SIJ etiology is approximately 15–20%.

PHYSICAL EXAMINATION AND DIAGNOSTIC TECHNIQUES

Evaluation of the SIJ should be part of a complete spine evaluation in all patients presenting with LBP as much to determine a diagnosis of SIJ pain as to evaluate differential diagnoses. The potential anatomic sources of pain and their relative prevalence in patients with axial back pain include the intervertebral discs (5–39%) and the zygapophyseal joints (15–40%), in addition to and less commonly the SIJs (6–16%).^{1,27,28} The physical examination of these patients is focused on delineating which of these structures is more likely to be the source of pain in a particular patient. Although pathology of each of these structures can result in LBP, their manifestations do have subtle differences that can aid the evaluating physician in forming an appropriate diagnostic algorithm and determining further workup.

Risk factors signifying altered SIJ loading or a history of trauma can identify the subset of patients complaining of LBP who might have pain from the SIJ. For example, activities that involve unilateral loading, i.e. kicking and throwing, place people at increased risk, as do altered spinal alignment and posture, for similar reasons.²⁹ Trauma, including physiologic hypermobility with pregnancy, has also been identified as a risk factor for the immediate or delayed presentation of SIJ pain.^{29–31}

The pattern of pain originating from the SIJ is somewhat different from discogenic or facetogenic lumbar spine pain. Typically, SI pain occurs below the waistline and is more commonly unilateral than bilateral (4:1) in nature.³² There are numerous provocative tests described in the literature, the most reliable and valid of which seem to be the

FABER, POSH, and Gaenslen's tests.³³ All of these tests are performed with the patient supine on the examination table. The FABER (Flexion, Abduction, External Rotation), or Patrick test, is performed by first flexing, abducting, and externally rotating the hip, and then moving it to an extended position. The POSH (Posterior Shear) test is performed by flexing the hip to 90°, adducting the hip slightly, and applying a posterior axial load to the femur. The Gaenslen's test is performed by maximally flexing one hip and concurrently maximally extending the contralateral hip. Pain in the posterior pelvic region over the SIJ in any of these three provocative tests may indicate an SIJ etiology.

Early studies looking at the validity of SIJ physical exam tests were disheartening, demonstrating poor validity and low reliability; however, these studies often evaluated one test in isolation and used a 90% threshold reduction in pain with injection as the comparative gold standard, which is somewhat limiting.³⁴ More recently, researchers have evaluated these tests in combination, and by comparing them to a more reasonable gold standard, pain relief threshold of 70% with injection, they have found more encouraging results. Reliability of the POSH, FABER, and Gaenslen's tests with the more reasonable injection relief threshold was higher than 80% and the POSH test in particular had the highest sensitivity and specificity.³⁴ Cibulka et al. evaluated the utility of these tests in combination and found that multiple provocative tests, as one would expect, improve utility with sensitivity, specificity, and positive predictive value all over 80%.³⁵

Intra-articular anesthetic SIJ injections are the closest thing to a gold standard similar to the case with discogenic and facetogenic back pain. Although there are few well controlled studies evaluating these tests, Rupert et al. recently performed a systematic review of the literature and reported level II evidence for the validity of SI diagnostic joint injections.³⁶ This was confirmed in more recent studies, which concluded these injections to be the most useful studies for SIJ dysfunction.³⁷ As is the case with other diagnostic injections, the patient reported quality and percentage pain relief following injections along with the duration of symptom relief implicates sacroiliac dysfunction for patients with suggestive symptoms.

IMAGING

Symptomatic sacroiliac dysfunction is not reliably demonstrated on any imaging study. Rather, the role of imaging

in the evaluation of patients with LBP and a possible sacroiliac etiology is to rule out other anatomic sources of back pain and more atypical etiologies of pain such as tumor, infection, and sacroiliitis. Plain radiography is often a first step in diagnostic imaging. The orientation, irregular surface, and complexity of the SIJs make the utility of plain films minimal in the absence of dramatic pathology. Ossification and degenerative changes can often be picked up on patients of increasing age, though there is no clear correlation between these findings and symptoms in the literature.³⁸

Computed tomography (CT) can better visualize degenerative bony changes, osteophytes and joint space narrowing, though again, there is no clear relationship to symptomatic SI dysfunction.³⁹ In the case of patients with acute or subacute symptoms along with history of trauma, CT can reveal more subtle fractures not demonstrated on plain films.

Functional imaging like bone scintigraphy or single-photon emission computed tomography (SPECT) can demonstrate inflammation in addition to other pathology and has been shown to have rather high specificity for SIJ disease.⁴⁰ Slipman et al., however, also demonstrated that the sensitivity of these studies is as low as 13%, making the utility of this type of imaging as a screening test for SIJ dysfunction quite minimal.

Magnetic resonance imaging is useful for both its functional imaging component, which can demonstrate inflammatory changes and stress fractures etc., and its ability to demonstrate fine anatomic detail. In patients with sacroiliitis from spondyloarthropathies, MRI is useful for detecting the subtle changes in the dorsal synovial aspect of the joint that represent earliest stages of SIJ involvement and occur prior to any radiographic changes.⁴¹ Similar to other advanced imaging techniques for this application, the concordance of MRI findings with symptomatic SI dysfunction has not been demonstrated and MRI is again most useful for ruling out other etiologies of LBP. Analogous to discogenic back pain, the diagnosis of SI dysfunction is difficult and relies on a combination of patient history, symptoms, and physical exam findings as a screening tool, while imaging serves more to detect and rule out other pathologies.

■ NONOPERATIVE MANAGEMENT

The management of SIJ pain is controversial and there are few high-quality studies comparing different modalities.

That said, SIJ pain management should take a two-pronged approach, with the goals of both providing symptomatic relief and addressing the underlying pathology. Several authors have discussed the nonoperative management of SIJ dysfunction in terms of acute phase (<3 days), recovery phase (3 days to 8 weeks), and maintenance phase (>8 weeks).⁴²

Patients in the acute phase of SI pain, like other acute musculoskeletal injuries, can benefit from relative rest, which is not equivalent to immobilization, as well as anti-inflammatory medications and cold therapy. In patients whom pain persists well into the recovery phase and beyond, other pathologies should be ruled out with physical exam and diagnostic studies as previously discussed. Further, these patients with persistent or recurrent symptoms should be evaluated specifically to rule out leg length discrepancy, spinal deformity, or gait abnormality, all of which can result in altered SI biomechanics and painful SIJ dysfunction and are amenable to specific therapies.

Physical therapy is aimed at the correction of asymmetries in stiffness and strength as well as exercise-induced lumbopelvic stabilization programs. Mooney et al. evaluated patients with SIJ dysfunction and found that they had EMG abnormalities in the pelvis stabilizing muscles that normalized with stabilization programs and were concordant with relief of their clinical symptoms.⁴³ SIJ stabilization can also be augmented with the aid of orthotics, such as SI belts, which were demonstrated to provide symptomatic relief specifically in patients with laxity resultant from multiple pregnancies.⁴³ Sasso et al. looked at 69 patients with symptomatic SI dysfunction and found that at 2 years, 95% had sustained good or excellent results with a structured physical therapy program alone.⁴⁴

Intra-articular steroid and local anesthetic injections have both a diagnostic and a therapeutic role for patients with symptomatic SIJ dysfunction and have been thoroughly investigated, with most studies demonstrating good to excellent pain relief lasting on average between 6 months and 1 year.^{45,46} The differential role between intra- and periarticular pathology has not been completely borne out in the literature, though Borowsky et al. did show improved pain relief in patients receiving intra- and periarticular combination injections relative to intra-articular injection alone.⁴⁷ These injections should be utilized sparingly, as with other intra-articular steroid injections, and as part of a combined approach incorporating physiotherapy, activity modification, and anti-inflammatory medications.

SIJ denervation procedures, most recently performed with radiofrequency ablation (RFA), have also received some attention in the literature and have been shown to have some limited success that is rather similar to that of intra-articular injections.⁴⁸ Perhaps secondary to the complex and redundant innervation of the SIJ, a number of patients have recurrence of symptoms between 6 and 12 months after denervation therapy. Nonetheless, these procedures merit further investigation and may become increasingly efficacious as we further elucidate SIJ innervation and refine RFA techniques.

■ OPERATIVE MANAGEMENT

Sacroiliac joint arthrodesis was utilized quite commonly in the early 1900s as a treatment for low back and buttock pain prior to Mixter and Barr's discovery of the herniated disc and the subsequent shift of focus to the disc as a primary etiology of back and leg pain. Sacroiliac joint arthrodesis is most commonly performed today for pelvic ring instability secondary to trauma and has been achieved through a number of techniques including uninstrumented bone grafting, anterior plating, and sacroiliac screws, in addition to other less frequently employed constructs. Studies evaluating outcomes after SI arthrodesis for isolated SI dysfunction are limited, as the vast majority of patients will respond to less invasive modalities such as physiotherapy and injections.

Waisbrod et al. performed 22 uninstrumented SIJ fusions for painful osteoarthritis and demonstrated a 70% rate of satisfactory results at follow-up between 12 and 55 months.⁴⁹ More recently, Buchowski et al. described a consecutive case series of 20 patients who underwent SIJ arthrodesis for symptomatic SI dysfunction diagnostically confirmed by good response to intra-articular injection.⁵⁰ Patients performed SF-36 forms preoperatively and postoperatively at final follow-up averaging 5.8 years. Patients demonstrated statistically significant improvement in nearly all categories including physical functioning and pain indices, and 85% of patients demonstrated solid fusion visible on plain radiographs. In recent years, the SIJ has gained increasing attention and minimally invasive fusion techniques for SI arthrodesis are being developed. Wise et al. performed SI arthrodesis in 13 patients using percutaneously placed fusion cages filled with bone morphogenetic protein-2 (BMP-2) and demonstrated a fusion rate of 89% with an average improvement of

4.9 points on the 10 point visual analog scale (VAS) at mean follow-up of 29 months.⁵¹

■ DISCUSSION

Sacroiliac joint dysfunction is an insufficiently understood clinical entity, owing both to the joint's highly specialized and unique anatomy and biomechanical properties and its complex innervations. The role of the SIJ in back pain has ranged the spectrum from primarily a focus on discogenic causes of LBP leading to little attention to the SIJ in the last 50 years as a cause of LBP to a more recent focus. Prevalence data, however, demonstrate that 15–20% of patients who present with LBP have symptoms originating from the SIJ. Given that abnormal lumbar spine MRI findings exist in a significant portion of asymptomatic patients, practitioners must be thoughtful about the potential for symptomatic SIJ dysfunction so as not to focus interventions on a potentially asymptomatic imaging finding elsewhere and ignore a painful SIJ.

The diagnosis of SI dysfunction in the context of LBP can be difficult, but SI pain has several qualities (below the belt line and often unilateral) that distinguish it from other common etiologies of LBP. Further, positive response to several provocative SIJ tests makes the positive predictive value for SIJ pain above 80%. If diagnosed appropriately, 95% of patients will improve with physical therapy and intra-articular SIJ injections. In the minority of patients with chronic debilitating SIJ pain that does not respond to nonoperative management, arthrodesis is an increasingly recognized potential treatment option. Novel techniques and instrumentation for minimally invasive and percutaneous SIJ fusion have yielded good early results with low complication rates and favorable outcomes. Clinicians, and spine surgeons especially, must shift some focus back to the SIJ in order to better care for the 15–20% of patients that walk into the office with LBP and have painful SIJ dysfunction.

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Tarlov Cysts

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Snapshot

- » Pathophysiology
- » Clinical Presentation
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INTRODUCTION

Dr Isadore M Tarlov was the first to recognize and describe perineurial cerebrospinal fluid (CSF) cysts. During his extensive cadaveric dissection of 30 terminal filum specimens at the Montreal Neurological Institute in 1938,¹ Dr Tarlov examined cysts that were found anatomically at the junction of extradural space and the posterior nerve of the respective dorsal root ganglion in 5 of the 30 cadavers. These perineurial cysts, localized specifically at the endoneurial-perineurial junction, were later named after Dr Tarlov to honor his extensive histopathological evaluation work.¹

Following Dr Tarlov's discovery, various authors attempted to further describe and characterize spinal cysts. In 1987, Goyal et al. clarified intraspinal cysts by classification into these five distinct categories: (1) perineurial cysts, also known as Tarlov's cysts or "nerve root diverticula,"² (2) nerve root sleeve dilations, (3) *intradural arachnoid cysts*, (4) *extradural arachnoid cysts*, and (5) *traumatic nerve root cysts*.

An even more simplified classification of spinal meningeal cysts was offered in 1988 by Nabors et al.:

- *Type I* (extradural meningeal cysts *without* spinal nerve root fibers)

- *Type II* (extradural meningeal cysts *with* spinal nerve root fibers)
- *Type III* (spinal *intradural* meningeal cysts).

Tarlov's cysts are Type II meningeal cysts, as classified by Dr Nabors. In fact, a Tarlov's cyst requires histopathological evidence of inclusion of spinal nerve root fibers to confirm its diagnosis.³

The prevalence of Tarlov's cysts is estimated at 1–4.6% in adult populations.⁴ Pertaining to gender, there does appear to be a slight predilection for the female population. Tarlov's cysts are more commonly seen in *young* adults. Specifically, 4% of patients with incidentally discovered lumbosacral lesions are less than 50 years of age whereas 1.3% of patients are >50 years of age.⁵ With improvements in and increased utilization of neuroimaging, the incidental finding of perineurial cysts continues to escalate.

PATHOPHYSIOLOGY

Tarlov's cysts are described as saccular, hollow lesions composed of nerve tissue containing CSF. From the time of Tarlov's original cadaveric studies, multiple hypotheses regarding pathogenesis have been offered.

Dr Tarlov's theory stemmed from his discovery that abundant inflammatory cells were embedded in the cyst

wall and adjacent tissues. As a result, Dr Tarlov felt that the pathogenesis of perineurial cysts was due to nerve root inflammation coupled with CSF inoculation. His second theory, developed following his work with the delayed oil-based contrast myelography studies, was that the inflammatory process may facilitate the sealing of meningeal diverticula, leading to the development of a symptomatic meningeal cyst. His ultimate theory was that trauma induces hemorrhage and leads to cystic degeneration and blood product deposition in the form of hemosiderin, which then leads to destroyed neural tissue or ischemic degeneration, and ultimately leads to breakage of venous drainage at the perineurium and epineurium and secondary infiltration of CSF.⁶⁻⁹

Additional theories proposed by Haddad, Strully and Heiser coincide with Tarlov's later theory. They hypothesized that dural lacerations following spinal surgery trigger pseudomeningocele formation. Park et al. argues that Tarlov's cysts have a significant genetic component and may develop secondary to congenital dural weakness or persistent embryonic fissures.^{5,10} Tarlov's cysts have also been associated with other congenital and connective tissue disorders as well as nerve root sheath duplications.⁷

In 1947, the Swedish anatomist, Bror Rexed, concurred with Tarlov's theory that cysts occur secondary to arachnoid mater overproliferation, followed by closure of the communication between the subarachnoid space and overproliferative arachnoid, ultimately leading to cyst formation.^{11,12} The most recognized pathophysiologic explanation includes perineurial cyst development secondary to microcommunication between the cyst cavity and subarachnoid space specifically at the endoneurial-perineurial junction of the nerve root dural sleeve. It is thought that pulsatile and *hydrodynamic* forces as well as compromised sheath integrity at this anatomical point may contribute to the development of a one-way ball-valve effect. Cerebrospinal fluid influx is permitted and CSF efflux is restricted, leading to gradual expansion of cyst size. As a result of the ball-valve phenomenon, we often see Tarlov's cysts located at the junction of the posterior nerve root and dorsal root ganglion.^{3,13} This theory of a one-way valve supports the observation that large Tarlov's cysts cause progressive neurological symptoms as they distort, compress or stretch the adjacent spinal nerve root. Less commonly, there is progression to erosion of adjacent sacral bone.¹⁴ In addition, this may lend itself to periosteal pain fiber irritation and subsequently insufficiency fractures.¹⁵

CLINICAL PRESENTATION

Tarlov's cysts as originally described by Dr Tarlov were asymptomatic; however, later in his studies he speculated that sacral radiculopathy may present as a common symptom. Dr Tarlov's initial paper was his most widely read and cited, and as a result, his initial impressions persisted for some time. Tarlov's cysts often present as small, multiple, and extending around the circumference of nerve roots within the sacral region especially at the sacral 2-3 nerve roots and therefore present with radiculopathy at the sacral 2-3 level.^{16,17} Nevertheless, Tarlov's cysts have been found to occur along any segment of the spinal cord.⁶

Large cysts and symptomatic cysts are quite rare. It is estimated that only 1% of Tarlov's cysts become large enough to cause symptoms related to local compression.^{4,5,18} However, it is thought that 17% may have an additive effect on other neuropathologies such as degenerative disc disease.¹⁸ Nonetheless, the natural history of these cysts is to enlarge, leading to progressive symptoms. The most common symptoms include sensory disturbances such as dysesthesias, lower back pain, sacral radiculopathy, and neurogenic claudication.¹⁹⁻²¹ Other common symptoms include bowel and bladder dysfunction, sexual dysfunction, and lower extremity motor weakness.^{8,22-24} Less commonly, a patient may present with intracranial hypotension if the cyst has ruptured, lending itself to positional headaches. There are numerous case reports of Tarlov's cysts presenting with common symptoms of physiologically distinct systems. One case report described a presacral cyst found via gynecological transvaginal ultrasound after the patient presented with pelvic pain.²⁵ Interestingly, Tarlov's cysts are often seen in the female population (for unknown reasons) and it is speculated that there may be a reluctance among female patients to fully disclose the entirety of pelvic symptoms to spine specialists (mostly men), and this may have perception of the medical significance of Tarlov's cysts throughout history.²⁶ One might elicit a history of exacerbation of pain with coughing, standing, and changing of position. These symptoms serve to prove the aforementioned pathologic theory of the ball-valve phenomenon, wherein an increase in CSF pressure induces a mechanic pressure to spinal nerve roots and activates neurogenic symptoms. Alleviation of symptoms is present in the recumbent position. Lastly, very rarely, thoracic Tarlov's cysts have been described to elicit angina-like symptoms.²⁷

DIAGNOSIS

Tarlov's cysts are often detected incidentally during spinal computed tomography (CT) or magnetic resonance imaging (MRI). Langdown and colleagues reported that 70% of Tarlov's cysts detected by MRI were found to be asymptomatic, whereas only 13% were found to be symptomatic. With the increased usage and reliance on MRI for symptoms such as lower back pain, spinal radiculopathy, and lower extremity weakness, the incidence of incidental meningeal cyst diagnosis is on the rise; other common incidental findings during lumbosacral imaging include vertebral hemangiomas, fibrolipomas, synovial cysts, and sacral meningoceles.²⁸ MRI, the imaging modality of choice for diagnostic purposes, also aids in surgical planning through its high enhanced resolution of tissue density, multiplanar capabilities, and characterization of the cyst and surrounding structures. Tarlov's cysts appear as round, well-circumscribed masses. T1-weighted images reveal low signal while T1-weighted images reveal high signal, coinciding with radiographic characteristics of CSF.^{4,29,30} The cysts often extend to envelope nerve roots and may reveal impinge on neighboring nerve roots.³¹

Computed tomography (CT) is helpful for visualization of the vertebral body and posterior elements that will show scalloping, rounded paravertebral shadow or insufficiency fractures. The cyst appears isodense with CSF on noncontrast CT studies. CT may also be used for image guidance during percutaneous aspiration.⁴ Plain radiographs are often negative for pathology; however, in the late stages, severe bony erosion of the vertebral body or neural foramina may be visualized.

Myelography is often utilized in diagnosis, especially when MRI is contraindicated. More importantly, myelography with delayed CT has greatly advanced our understanding of the pathophysiology of Tarlov's cysts.

Although a slightly more invasive imaging modality, direct visualization of filling patterns can lead to diagnosis.³³ Shrieber and Haddad were one of the first to describe the characteristic delayed filling pattern using oil-based pantopaque contrast-enhanced myelography. Here, the oil-based contrast was not immediately visualized but was seen hours, days or even weeks later.³³ Later utilized by Dr. Tarlov with works published in 1970, he was able to determine the difference between meningeal diverticula and Tarlov's cysts.

Computed tomography conducted 30–60 minutes after intrathecal contrast administration can reveal delayed filling of meningeal cysts. From this imaging, one can conclude that there is a microcommunication between the cyst cavity and the subarachnoid space, lending itself to a very slow hydrodynamic process coinciding with the valved phenomenon. Other authors adopt the CSF transudation theory, which proposes that CSF migrates across the cyst wall membrane into the perineurial cyst cavity. Additional claims include a lack of true communication with the spinal subarachnoid space and that detection of myelographic defects is extra-arachnoid in nature.^{2,6,34} This is contrary to meningeal diverticula, which are in free communication with the subarachnoid space and rapid fill during myelography.²² This is an important diagnostic pearl as meningeal diverticula are less likely to produce symptoms. In addition, meningeal diverticula often appear proximal to the dorsal root ganglion at multiple thoracic levels. Tarlov's cysts may appear in multiple locations throughout the lumbosacral spine but usually appear extradural and directly at or immediately distal to the junction of the posterior nerve root and dorsal root ganglion.^{8,22} (Table 89.1 from Acosta et al. regarding Tarlov's classification of spinal cysts).

Although imaging can suggest the diagnosis of a meningeal cyst through radiographic features, Tarlov's

Table 89.1: Tarlov's classification of spinal cysts.*

<i>Lesion</i>	<i>Communication W/SS</i>	<i>Filling pattern on myelography</i>	<i>Location along nerve root</i>	<i>Nerve fibers W/in cyst</i>
Perineurial cysts (Tarlov cysts)	No	Delayed filling	At or distal to junction of pst nerve root and DRG	Yes
Meningeal diverticula	Yes	Rapid filling	Proximal to DRG	No
Long arachnoidal prolongations	Yes	Rapid filling	Continuous prolongation of SS over nerve root	NA [†]

*NA: Not applicable; pst: Posterior; SS: Subarachnoid space.

[†]Although these can be confused with meningeal diverticula and perineurial cysts, arachnoidal prolongations are not actual cystic lesions.

cysts require a histopathologic diagnosis to show the presence of nerve fibers, ganglionic cells, and possibly old microhemorrhages in the form of hemosiderin.⁷ One must visualize neural fiber involvement. The meningeal cyst walls are composed of perineurium. In a histopathologic study, the outer cyst wall is formed of vascularized connective tissue whereas the inner cyst wall contains flattened membranous arachnoid tissue. Peripheral nerve fibers and ganglionic cells can be found embedded into the cyst wall.⁸ Nerve roots are found within the cyst wall in about 75% of all Tarlov's cysts.⁷ In addition, nerve roots are also seen to lie within the actual cyst cavity.

Rarely performed adjunct studies include electromyography and nerve conduction studies, which may exhibit decreased sural nerve action potentials and sensory nerve conduction velocity loss.³⁵ Motor nerve conduction studies are often normal, which coincides with the location of most Tarlov's cysts adjacent to the dorsal root ganglion. Urodynamic studies can evaluate for bladder dysfunction.

TREATMENT OPTIONS

There is no gold standard or clearly defined criteria for surgical or conservative management of Tarlov's cysts. There are no published data with regard to the natural history of Tarlov's cysts. As a result, clinical judgment is of the utmost importance in determining the etiology of the patient's symptoms and whether the meningeal cyst is a likely cause. General consensus remains that if the patient is symptomatic, treatment is recommended. This consensus is challenged when a second pathology is present, such as disc protrusion or neuroforaminal stenosis. At this point, the clinician must determine which pathology is most likely the cause. Once the decision is made to treat, typical conservative spinal management is recommended in the form of analgesics such as nonsteroidal anti-inflammatory medications and the tricyclics, especially nortriptyline and desipramine, as these have the highest therapeutic index and are inexpensive.²⁶ Second-line medications include gabapentin and opioids. In addition, conservative measures include physical therapy, oral steroids, and finally, epidural steroid injections. Langdown's case series of Tarlov's cysts treated conservatively exhibited a 3.3 median year follow-up radiograph showing no changes to the cyst features.¹⁸ After a significant period of failed therapy, more invasive measures are suggested.

There is a myriad of proposed surgical strategies. Surgical approaches can be organized into two major subtypes: CSF flow diversion and surgical decompression.

CEREBROSPINAL FLOW DIVERSION

Options include: external CSF drainage,³⁶ percutaneous cyst drainage,^{4,37} percutaneous fibrin glue injection,^{38,39} insertion of a cyst-subarachnoid shunt,⁴⁰ cyst-peritoneal shunt,³⁹ or lumboperitoneal shunt.⁴⁰ CT-guided percutaneous aspiration of cyst fluid is fraught with all the pitfalls of cyst aspiration in other parts of the body. The fluid always reaccumulates as long as the cyst wall remains intact, and therefore symptoms often recur. There are multiple published series of Tarlov's cysts treated with percutaneous cyst aspiration followed by percutaneous fibrin glue administration. Original studies showed improvement in symptoms after the first 6 months. However, 75% of the cases developed postprocedural aseptic meningitis.³⁸ Repeat studies showed 80% improvement in symptoms after 23 months; however, there were still two cases of transitory postprocedural aseptic meningitis.²³ The largest retrospective study of 122 patients conducted by Murphy et al. showed symptomatic improvement in 65% of the patients, with 23% symptomatic recurrence rate after only 7 months.³⁰ As a result, the general consensus among authors is that percutaneous cyst aspiration, with or without fibrin glue injection, has clinical utility.

Given the pathophysiology one-way pressure valve theory, one treatment measure aims at decreasing the pulsatile pressure cephalad to the cyst valve, thereby decreasing the size of the cyst, thereby relieving impingement of the nerve root. This is done via lumboperitoneal shunting. Vartels and associates reported that two patients with leg and back pain who were treated with lumboperitoneal shunt found symptomatic relief after a median of 10 months. Often this procedure is suggested for patients with multiple cysts, where the cause of the symptomatology is difficult to determine. Nevertheless, as with all shunts, there is an added risk of malfunction and infection. Cysto-subarachnoid shunts are used primarily as an adjunct to microsurgical decompression to equalize pressures without requiring cyst wall resection and encountering complications of neurological sequelae from neural fiber resection. The CSF flow diversion techniques may also serve as a more minimally invasive diagnostic measure when there is a question about the clinical significance of the cyst. Nevertheless, many argue that the best long-term results are yielded with a more aggressive surgical approach.²²

SURGICAL DECOMPRESSION

Tarlov originally advocated for complete cyst removal with excision of complete posterior nerve root and ganglion.

This was utilized for many years following Tarlov's original work; however, resulting morbidity including significant neurological deficits led many to seek other options. Simple posterior sacral bony decompression via laminectomy was proposed and yields mild morbidity but has low success rate as well as complications such as durotomy or neurotomy. Microsurgical excision involves laminectomy with microsurgical cyst wall manipulation. Various procedures include: imbrication (which involves suturing of the cyst wall),⁴¹ cyst neck ligation (which closes communication between the cyst cavity and intrathecal sac), cyst fenestration (which also opens the communication between intrathecal sac and cyst cavity), and lastly cyst wall resection (which often involves sacrificing the nerve root). There have been published reports that show very low morbidity with laminectomy and,^{7,42} cyst neck ligation,^{42,43} cyst wall resection,^{7,9,31} and cyst imbrications, cyst fenestrations and bipolar cautery to shrink the size of the cyst.^{2,3,43,44} Meticulous surgical planning is of utmost importance. Often, a simple laminectomy via standard posterior approach with careful en masse excision of the cyst wall is the option of choice. Neural elements are often involved and the neural sheath must be excised.

PATIENT SELECTION

The clinical indication for surgery has been studied by a very few. Voyadzis and associates presented cyst diameter criteria for surgical treatment. Cysts greater in diameter than 1.5 cm, with associated radicular or bowel/bladder dysfunction, tended to improve at a better rate.^{7,45} Multiple cysts, as well as mega cysts, (> 1.5 cm) were associated with significant greater morbidity. Neulen et al. showed that patients with single or multiple perineural cysts > 1 cm in diameter with delayed filling seen on postmyelographic CT scan were likely to benefit from surgical intervention. Pain associated with Valsalva and postural maneuvers was shown to likely benefit from surgical decompression.⁹

Kunz and associates evaluated surgical treatment of Tarlov's cysts and compared it to conservative treatment. In a study of 16 patients, they ascertained that there is no clinically significant difference in symptomatic improvement between conservative and surgical treatment because of the associated postsurgical pain. As a result, surgical intervention should be recommended only for a patient with a significant neurological deficit as well as a short history exacerbated by postural changes.

PREOPERATIVE WORK-UP

Magnetic resonance imaging of the lumbosacral spine should be obtained for every patient. In addition, myelography with delayed CT is useful in distinguishing between meningeal diverticula. A CT scan will help disclose any bony erosions and instability that may require operative stabilization.

TECHNIQUE

Careful dissection using nerve root retraction and penfield is pertinent. Often, neural elements are involved within the cyst. One should take great care to maintain nerve root and nerve sheath without excision. However, such as in the case of Sen et al., this does not always correspond to residual neurological deficits. With large cysts, ligation of the neck precedes en masse excision.⁴⁶

Often, an intraoperative Valsalva maneuver is utilized to exhibit CSF flow through the posterior nerve root sheath into the cyst.²⁵ In addition, surgical cyst fenestration and imbrications with the use of electrophysiological monitoring and the use of fat or muscle grafting to reinforce closure^{9,22} are proposed.

The specimen should be sent to pathology to evaluate for inclusion of neural elements confirming the diagnosis of Tarlov's cyst.

POSITIONING AND ROOM SETUP

The patient should be positioned prone in natural alignment on a standard operating room table with a supporting frame, such as the Wilson™ Frame by Mizuho to maintain the patient in a flexed position. A midline incision over the sacral prominence along the lines of Langerhan is created with the guidance of multiplanar fluoroscopy. The incision length should extend from L5 to S3 approximately 5 cm in length incision, depending upon the size and location of the cyst. Using an 11'-blade needle, the skin and subcutaneous should be sharply incised in the midline with careful dissection through the paravertebral musculature to the subperiosteum of the sacral spinous tubercles. At this point, the sacral roof will be encountered. The blue-hued cyst may be visualized beneath the sacral lamina, especially when there is significant bony erosion and the bone is thinned. Monopolar cautery may easily fracture the thinned bone and should be utilized with caution. Preoperative planning for the bony window should be created through visualizing cyst boundaries on high-resolution thin-cut CT with the ultimate goal of exposure of sufficient cyst.⁴⁷ When the cyst is large enough, it is not necessary to fully expose the

range of cyst. Pertinently, adequate exposure includes visualization of the cephalad–thecal sac.⁸ A high-speed drill is used to create bilateral sacral troughs, which are then connected through horizontal linear cuts of the sacral roof. These cuts should lay rostral and caudad to the cyst. The sacral window is then elevated as one piece with careful preservation of the integrity of the cyst wall roof. The bone should be saved for closing and plating.

The microscope should be positioned at this point. Microsurgical decompression aims to serve three important purposes: (1) decompress yet preserve surrounding nerve roots, (2) halt bony erosion, and (3) obliterate any persistent connection between the lumbosacral cistern and the cyst cavity. As previously stated, electrophysiologic monitoring is helpful during dissection of the cyst wall from the sacral nerve roots, which tend to travel adjacent to or through the cyst. Prior to cyst fenestration, the cyst should be thoroughly evaluated for the presence of adjacent nerve roots. Once a safe region for transection is identified, the microscissors are used to open the cyst and aspirate the contents. This will result in the cyst's collapse. Imbrication of the cyst's wall can be utilized if the remaining nerve root sheaths are not too fragile or attenuated. Attention should be now directed toward dissection with identification of any microcommunications with the subarachnoid space. The complete cyst wall should be resected and the dural sac should be respected. The cyst wall should be sent for pathologic evaluation of included neural elements.

Closure often requires local fat or muscle grafting, which is placed at the located communication to prevent future CSF leak. At this point, the anesthesiologist should be asked to stimulate Valsava pressure to ensure proper placement of the graft. Local muscle grafts are preferred because of their durability and longevity, as fat grafts tend to diminish with time. Enough cyst wall edge should remain to approximate the cyst wall edges superficial to adjacent graft placement. This should be performed with no absorbable suture in an interrupted fashion for tensile strength and permanence. Fervid cyst wall resection can lend itself to large defects, which may prove difficult to close. The layered closure may then include fibrin glue and/or dural graft matrix. The bone graft should then be repositioned en bloc and secured to the sacral lamina with titanium plates and screws. Some authors suggest placement of a subarachnoid lumbar drain for 7 days to prevent CSF leak; however, there is no current study to date to validate its use.^{9,43}

RISKS OF PROCEDURES

Complications after excision include infection, CSF leak, and neurological deficit. Surgical adjuncts include fibrin glue and absorbable gelatin sponge placement; muscle and fat grafting is used to fill the cyst or cover any dural defects. Nevertheless, there have been reports of neurological worsening and even more devastating sequelae such as cauda equina syndrome following translocation of grafts. Cerebrospinal fluid leakage is quoted as the most common complication and reported by Neulen et al. as present in 1 in every 13 patients, by Guo et al. as 1 in every 11 patients and as common as 1 in every 3 patients by Langdown et al.^{8,13,18}

COMPLICATION AVOIDANCE

Complication avoidance starts with patient selection. Patients with radicular symptoms, exacerbated with positional changes and Valsalva maneuvers or patients with bowel/bladdery dysfunction, benefit most from surgery. Electing proper surgical management in the form of complete cyst resection, if possible with minimal usage of surgical adjuncts, will decrease the likelihood of complications. Often, lumbar drainage is utilized for 3–7 days postoperatively to prevent CSF leakage. The use of intraoperative neuromonitoring, in the form of somatosensory evoked potentials, may minimize serious injury to sacral nerve roots during microsurgical excision.⁹ Close postoperative assessment is imperative when muscle flaps and fat grafts are utilized to quickly evaluate for translocation.

PROGNOSIS

The cyst recurrence rate is fairly low and ranges from 0% to 10%.^{8,13,43,48} Symptomatic improvement following microsurgical treatment varies from 38% to 100%. Interestingly, it appears as if most symptoms improve in >90% of cases.

However, radicular symptoms may not benefit from surgery as they are occasionally an indicator of permanent spinal nerve impingement and this may lend to chronic pain syndromes.

OUTCOMES OF TARLOV'S CYST SPINE SURGERY PROCEDURES

It is evident from the author's extensive literature review that surgical correction in the form of laminectomy, cyst

resection and duraplasty lends itself to complete or substantial resolution of the preoperative symptoms. Very rarely does the patient experience temporary or permanent worsening of his or her preoperative symptoms. Although the options for surgical cyst management are varied, often the proposed surgical management carries a low risk of postoperative neurological deficits. It appears that fibrin glue injections are more commonly associated with a smaller percentage of improvements. Cerebrospinal fluid leaks tend to be the most common complication of surgical repair. It should be noted that laminoplasty and replacement of the bony graft appear to support dural closure and decrease the chance of a CSF leak. Furthermore, this reconstitution of bone provides additional stability, eventually preventing future sacral insufficiency fractures.⁴⁹

CONCLUSION

Spinal meningeal cysts, more commonly known as Tarlov's cysts, are a documented cause of sacral radiculopathy and pain. They are common in the general population and best visualized with MRI and CT myelography. Usually asymptomatic, their symptoms can include sacral radiculopathy, dysesthesias and a myriad of unexpected symptoms, and therefore should be considered as part of a differential diagnosis of neurological symptoms in the setting of minimal degenerative disease. Tarlov's cysts are believed to be caused by congenital weakness, trauma or inflammation of the dura matched with disturbance of CSF hydrodynamics.

Historically treated with various techniques, laminectomy, cyst resection and duraplasty are the preferred treatments. Judicious use of myocutaneous flaps and fibrin glue is recommended. When preoperative planning with consideration of electrophysiological and lumbar drain placement is utilized, outcomes have proven favorable, with serious complications occurring at a very low rate. Patient symptoms of motor deficits and sacral pain show the most improvement with sensory deficit improvement occurring at a less common rate.

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Failed Back Surgery Syndrome

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Snapshot

- » Causes
- » Patient Evaluation with Failed Back Syndrome
- » Treatment Options

INTRODUCTION

Failed back syndrome (FBS), also known as failed back surgery syndrome (FBSS), is defined as persistent or recurrent chronic disabling lower back pain after surgery on the lumbosacral spine with or without sciatic symptoms.¹⁻⁴ The incidence of FBS ranges from 10% to 40% of all patients undergoing lumbar spine surgery, including discectomies, laminectomies, and posterior spinal fusions.¹ In addition, multiple nonoperative modalities are used, resulting in an overall higher rate of treatment costs.^{1,5} Success rates of subsequent surgeries are significantly less than the index surgery.^{6,7} Patients who undergo multiple lumbar spine surgeries tend to have greater leg pain, greater disability based on Oswestry disability score, higher unemployment, and lower health-related quality of life based on SF-36 and EQ-5D compared to other chronic conditions.^{1,5}

CAUSES

Failed back syndrome may arise as a result of several types of causes, including (1) patient factors, such as psychological illness, comorbidities, compensation or personal gain; (2) differential pathology, such as vascular claudication, osteoarthritis, or diabetic neuropathy; (3) surgical factors, including improper technique, incorrect surgery, wrong surgical level, or poor patient selection; (4) immediate postoperative complications, such as dural and nerve root injuries, infection, pseudomeningocele, or arachnoiditis;

and (5) long-term postoperative complications, including epidural fibrosis, pseudoarthrosis, and progressive disease. Failed back syndrome in most patients can be traced to multiple factors. However, each of these causes is discussed separately in this chapter and must be treated distinctly.^{1,7,8}

Patient Factors

Patient factors play a significant role in postoperative outcome. Preoperative psychological testing for significant factors is recommended to improve the success of a patient's outcome.

Psychosocial factors that increase the risk of lower function and dissatisfaction postoperatively include a history of psychiatric illness, including depression, anxiety, poor coping mechanisms, somatization and hypochondriasis; drug abuse and alcoholism; and limited social support or marital discord. Spine pathology can worsen these pre-existing conditions. In addition, personal injury claim, secondary gain or worker compensation claims all decrease the likelihood of a good or excellent postoperative outcome.⁹⁻¹² Patients with leg pain for >2 years, preoperative resting numbness and footdrop, decreased preoperative function, and regular preoperative use of analgesics demonstrated lower function and dissatisfaction postoperatively.^{13,14}

However, pretreatment physical findings, presurgical pain intensity, and activity influence have not been shown to affect outcomes.¹¹ In addition, when a surgically

treatable pathology exists, the likelihood of a satisfactory postoperative outcome is higher. Return to work status is also correlated with a patient's preoperative work status. Patients who are on long-term sick leave or receiving disability benefits are less likely to return to work. Consulting with an occupational physician can help return the patient to the workforce, and it is important to keep the patient in the workforce preoperatively. It is also important to give patients realistic expectations on their respective potential outcomes and to inform them that fewer will have complete pain relief or return to their pain level or function prior to the onset of their symptoms.¹⁵

Lumbar Preoperative Pathology

The differential diagnosis of lower extremity pain includes hip pathology (i.e. osteoarthritis, avascular necrosis and labral tears) and peripheral vascular disease. Patients with failed back syndrome also have a higher incidence of associated nerve entrapment syndromes, most specifically piriformis syndrome, that often present with symptoms similar to a disc herniation throughout their lower extremities.^{1,7,16} Patients with a primary source of pain other than the spine can demonstrate abnormal magnetic resonance imaging (MRI) findings. Up to 64% of asymptomatic patients have evidence of abnormal intervertebral discs and disc herniations, as well as findings of facet arthropathy, spondylolysis and spondylolisthesis, and central stenosis.^{17,18}

Elderly patients with arthritic spine conditions frequently have concomitant hip pathology.¹⁶ In patients with low back pain who presented at a spine clinic, almost 20% had a combination of spine with hip and sacroiliac (SI) pain, and almost 8% had only hip or SI joint pathology.¹⁹ Up to 10% had no abnormalities in the spine, hip, or SI joint. Another study demonstrated a prevalence of up to 32% of hip pathology, including osteoarthritis and avascular necrosis.²⁰ More specifically, disc degeneration of the upper lumbar intervertebral discs demonstrates an association with hip pain, and therefore it is important to differentiate the main cause of pain as changes may be present in both the hip and the spine.²¹ There is a significant association with degenerative disc disease in the lumbar spine and in the hip, although lumbar degeneration has been shown to precede osteoarthritis of the hip.²²

History and physical examination as well as radiographs and diagnostic testing are useful in localizing the

primary source of pain. Signs and symptoms of hip pathology include groin pain, buttock pain, decreased hip range of motion, and lateral thigh pain. Specifically, tenderness to palpation are signs of bursitis of the greater trochanteric, ischium, and iliopsoas. Greater trochanteric bursitis has tenderness to palpation at the lateral aspect of the hip over the greater trochanter. Ischial bursitis has tenderness to palpation directly over the ischial tuberosity and results in pain with sitting and resisted hip flexion. Iliopsoas bursitis is located in the anterior hip with tenderness to palpation below the inguinal ligament and pain with hip extension.^{23,24} Pain localized to the groin or buttock region is more common with isolated hip pathology. In addition, worsening pain with weight bearing, pain and decreased internal and external rotation of the hip can be detected by physical examination. Weight-bearing radiographs of the hips demonstrate decreased joint space, osteophyte formation, and subchondral sclerosis and cyst formation.^{16,25,26} An MRI arthrogram and intra-articular hip injections of steroids with symptomatic relief are highly sensitive and specific for hip pathology and should prompt a referral to a hip specialist.¹⁶

Piriformis syndrome is caused by piriformis pathology resulting in compression and neuritis of the sciatic nerve resulting in symptoms similar to lumbar radiculopathy with pain radiating down the posterior thigh and leg.²⁷⁻³² However, symptoms are usually specific to muscles distal to the piriformis innervated by the sciatic nerve.³⁰ Symptoms include hip and buttock pain, greater sciatic notch tenderness, worsening of symptoms with sitting for >20 minutes, and with activities that result in piriformis stretching such as cross-legged sitting or internal rotation of the leg during ambulation.³⁰ Over 80% of patients with piriformis syndrome present with radiculopathy and symptoms radiating down the leg.^{27,29} No significant association is noted between piriformis syndrome and lumbar pathology.²⁷⁻²⁹

Traditionally, physical examination findings of piriformis syndrome that recreate the patient's radicular symptoms including the Freiberg maneuver (passive internal rotation of the hip), Pace maneuver (resisted hip abduction and external rotation), the piriformis test (with the patient on their side, the hip is flexed to 60° and downward pressure is placed on the knee), and Beatty's maneuver (with the patient on their side, the patient holds their flexed knee off the table).²⁸⁻³⁰ Recently, the FAIR test (a combination of flexion, adduction, and internal

rotation of the hip) in combination with direct palpation over the piriformis muscle resulting in reproduction of the patient's symptoms has been shown to be highly diagnostic of piriformis syndrome.²⁷ Electromyography (EMG) findings will demonstrate no abnormalities in muscles proximal to the piriformis muscles, with various abnormalities in muscles distal to it. Electromyography can be combined with active maneuvers, including the FAIR test, to increase the reliability of the diagnosis of piriformis syndrome.^{30,33} Injection of anesthetic and steroid into the piriformis tendon has also been shown to be both diagnostic and therapeutic for piriformis syndrome. Treatment begins with extensive use of anti-inflammatory medication and physical therapy and rarely surgical intervention, involving the release of the piriformis insertion with the release of the sciatic nerve.²⁷⁻³¹

Intermittent claudication can be due to both vascular and neurogenic causes, both of which can present with similar symptoms and are frequently both present in patients.³⁴ Although it causes symptoms similar to lumbar spinal stenosis, peripheral vascular disease requires a completely different diagnostic and treatment approach.¹⁶ History and physical examination are paramount in discerning between neurogenic and vascular claudication as the primary cause of a patient's symptoms.³⁵ Abnormal low-extremity pulses usually spark the suspicion for a vascular etiology. However, the sensitivity of this is only 60%.³⁶ Other signs and symptoms include skin discoloration, ulcers, and hair loss in the lower extremities.¹⁶ Both neurogenic and vascular claudication frequently present with atypical signs and symptoms. Therefore, ancillary tests, including EMG or ABI, are important tools in

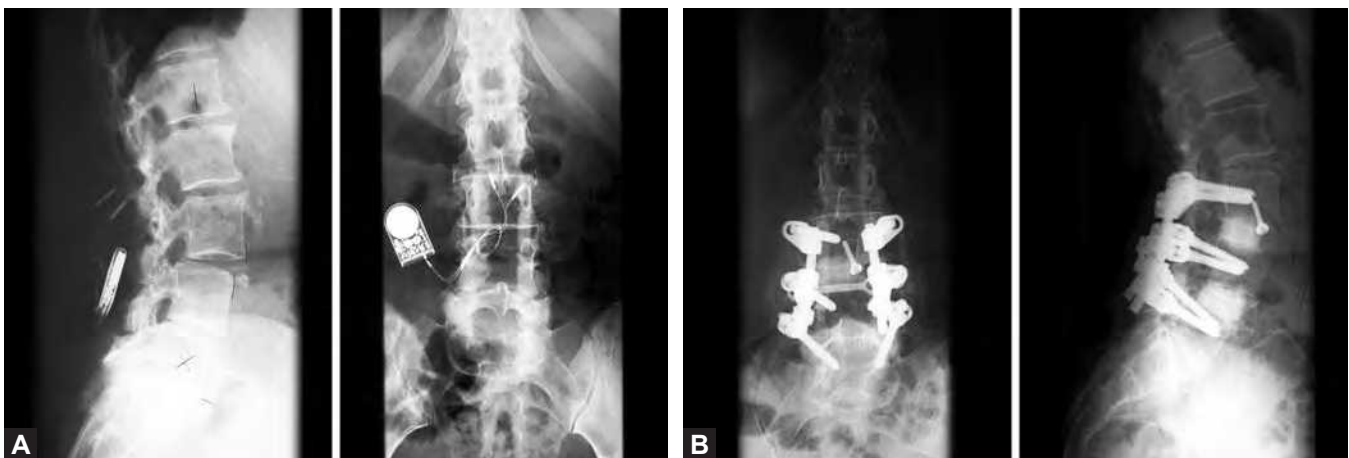
distinguishing the two when the history and physical examination are unequivocal.^{35,37} An ABI of <0.90 has a sensitivity and specificity of 85%, and the gold standard for diagnosis is a computed tomographic (CT) angiography.³⁷ Any of these findings should prompt a referral to a vascular surgeon for further evaluation and treatment.

Surgical Factors

Surgical factors can also be a cause of FBS. Surgical factors include inadequate decompression of the lateral recess and foramen, joint instability from excessive decompression, poor postoperative alignment, incorrect level and poor patient selection.³⁸⁻⁴¹

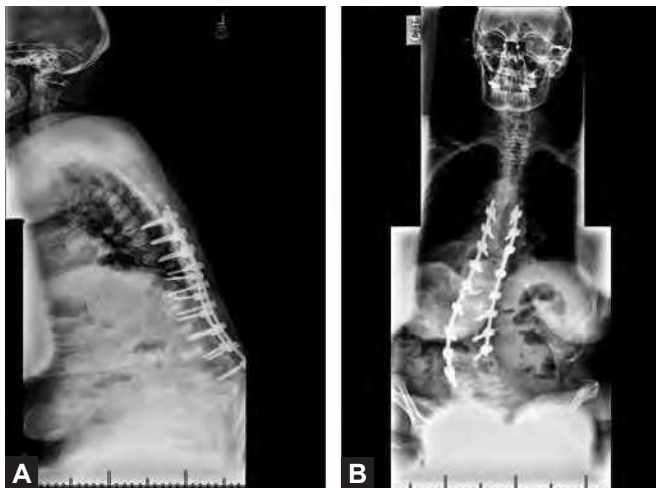
For patients who present with signs and symptoms of spinal stenosis, all areas of pathology should be identified, including central canal stenosis, lateral recess stenosis, and foraminal stenosis, and they should be thoroughly decompressed.⁴¹ Lateral recess stenosis and foraminal stenosis are the areas with the highest likelihood of residual stenosis causing continued postoperative pain.^{1,41} Those patients with identifiable continued stenosis have a higher probability of a successful second decompressive surgery.^{1,41} However, excessive decompression with excessive bone removal from the facet joint or the pars interarticularis can lead to instability and continued pain if no arthrodesis is performed (Figs. 90.1A and B). It is important to leave the pars interarticularis intact to not destabilize the spinal segment.⁴²

Both preoperative and postoperative sagittal alignment has been shown to correlate with postoperative surgical



Figs. 90.1A and B: (A) Postoperative instability following excessive decompression; and (B) Postoperative AP and lateral radiographs after anterior lumbar interbody fusion from L3-L5 and posterior spinal fusion with instrumentation from L3-L5.

success as well as degeneration of adjacent segments. Patients with decreased preoperative lumbar lordosis demonstrated significantly poorer results following laminectomy.⁴³ Patients with a postoperative normal C7 plumb line and normal sacral inclination demonstrated the lowest level of adjacent segment degenerative changes with a significant decrease in retrolisthesis of adjacent segments.²⁵ Postoperative flatback syndrome (Figs. 90.2A and B), also known as fixed sagittal balance and loss of lumbar lordosis, was originally described by Moe and Denis.⁴⁴ It was classically caused by Harrington distraction instrumentation into the lower lumbar spine due to distractive forces and a straight rod along the posterior elements of the spine.⁴⁵⁻⁴⁷ More commonly, it can result from failure to recreate lordosis during arthrodesis, development of pseudarthrosis or loss of correction, kyphosis at the TL junction, degeneration or decompression in adjacent segments, and hip flexion contractures.⁴⁷ Flatback syndrome results in compensation with hyperextension of other spinal segments, and flexion of the hips and knees to recreate horizontal gaze as well as spasm and atrophy of lower back muscles.^{40,47} In the long term, a flatback results in increased degeneration of adjacent segments and worse clinical outcomes.⁴⁸ Pseudarthrosis can be due to large forces applied to distal instrumentation with further caudal arthrodesis, with a greater increase when distal regional lordosis is not recreated during surgery. Proximally, thoracolumbar junctional kyphosis may also be due to failure to contour the rod.⁴⁷



Figs. 90.2A and B: (A) AP and lateral radiographs of postoperative flatback syndrome following posterior fusion with loss of lordosis and loss of sagittal balance; and (B) AP and lateral radiographs of following surgical correction of the flatback deformity with significant improvement in sagittal balance.

Identifying the surgical level is also paramount for success. Wrong-level surgery is unfortunately not uncommon in spine surgery. If the patient's offending pathology is not treated, surgery cannot be expected to result in significant relief of symptoms.¹ In patients with postoperative symptoms similar to their preoperative symptoms, inadequate treatment of the offending pathology should be ruled out as the source of the pain.

Patients with preoperative profound or progressive neurologic deficits are the best candidates for surgical intervention.⁴¹ However, most patients with chronic back and leg pain and nondiscrete neurologic deficits should be trialed with an extensive nonoperative course prior to surgical intervention as they have a lower likelihood of surgical success.⁴¹

Immediate Postoperative Complications

Immediate intraoperative and postoperative complications can increase the incidence of continued pain following surgery. These include nerve root and dural injuries, infection, pseudomeningocele, arachnoiditis, and paraspinal muscle injury.^{1,2,49} Damage to nerve roots both preoperatively and intraoperatively can lead to continued symptoms even following sufficient decompression.⁵⁰ Chronic compression by osteophytes and intervertebral disc material of nerve roots and of epidural veins, dilation of other epidural veins resulting in nerve root hypoxia, and perineural fibrosis can all lead to chronic nerve root damage.⁵⁰ Inadequate exposure intraoperatively can result in excessive nerve root retraction, resulting in further injury to nerve roots with chronic damage in addition to the changes already present.¹

Incidental durotomies have an incidence of 2–17% of spine surgeries, with a higher incidence in surgery in the thoracolumbar region, in women compared to men, with degenerative spondylolisthesis and juxtafacet cysts, and most significantly in revision surgery.⁵¹⁻⁵⁴ Immediate repair, with additional reinforcement using a collagen patch and fibrin glue with or without a nonaspirating drain, is the preferred treatment.⁵⁵ A Valsalva maneuver can be used to test the repair. The patient is also restricted to the supine position for 48 hours postoperatively and can ambulate per protocol as the patient's symptoms allow.⁵⁵ Failure rates for dural repair are <10%, with a significantly higher rate in revision surgery, up to 13%.⁵² A study evaluating 2-year outcomes following incidental durotomies demonstrated no difference in postoperative outcome. There was

no difference in long-term postoperative rates of infection, need for reoperation, neurologic injury, back or leg pain according to the visual analog scale, and no difference in functional disability based on the Oswestry Disability Index.⁵⁴

Postoperative infection is a devastating complication following surgery, usually requiring multiple repeat irrigation and debridement. The most common organism for postoperative spinal infection is *Staphylococcus aureus*.^{56,57} Risk factors for postoperative infections include older age, diabetes, elevated body mass index, American Society of Anesthesiologists (ASA) classification >2, serum albumin <3.5 g/dL indicating a diminished nutritional status, resident involvement, and procedures >300 minutes.⁵⁸⁻⁶⁰ The most significant MRI findings indicative of an infection included bony involvement and destructive characteristics.⁶¹ Treatment of a postoperative spinal wound infection requires aggressive irrigation and debridement and antibiotic therapy.^{56,59,62} If hardware is present, it is retained to maintain stability to the spine.^{56,59,62} Occasionally, repeat debridements are required, but primary closure is almost always possible.^{56,59,62} Patients infected with a history of diabetes mellitus (DM), methicillin-resistant *Staphylococcus aureus* (MRSA), bacteremia, presence of instrumentation, and allograft bone graft in the lumbar spine usually require multiple irrigation and debridements.⁶³ Patients with infections that are treated demonstrate significant improvement in disability outcomes and back and leg pain 2 years following their index procedure and with resolution of their infection.⁶⁴ However, disability outcomes, back and leg pain were all significantly worse than those patients without an infection.⁶⁴ Approximately 10% of patients in one study demonstrated pseudarthrosis in long-term follow-up.⁵⁶ In addition, a significant number of patients did not achieve a clinically significant improvement in their disability score.⁶⁴ Although patients did demonstrate improvement, patients with infections have a higher rate of back pain and decreased incidence of improvement in their disability indices.⁶⁴

A pseudomeningocele is an extradural collection of cerebrospinal fluid (CSF). It is the result of CSF leaking through the dura usually as a result of a dural tear, and can be encased with an arachnoidal lining.⁶⁵⁻⁶⁷ A pseudomeningocele contains CSF and communicates with the subarachnoid space. A CSF fistula can also occur following an unintended durotomy.⁶⁸ The MRI findings include thecal sac communication, absence of mass effect, low T1 signal, and low T2 complexity.⁶¹ If not identified and

corrected, it can lead to wound swelling, headaches, radiculopathy and other symptoms of a dural tear.^{65,66} The best prevention of this is meticulous, watertight closure of any observed or suspected dural tear. Treatment of a pseudomeningocele involves CSF diversion by lumbar drainage. Treatment of CSF fistulas consists of oversewing the wound. These approaches have been shown to be effective treatments without neurological compromise. The gold standard for treatment is reoperation with watertight primary closure of the dural tear.⁶⁸

Arachnoiditis is the inflammation of the arachnoid mater, one of the three coverings of the central nervous system.^{69,70} Arachnoiditis leads to a myriad of clinical manifestations. One of which is chronic pain syndrome with a varying constellation of symptoms. There is no consistent and unifying symptom, as patients who suffer from the disease display differing symptoms with varying degrees of severity. Symptoms can range from mild tingling to severe motor involvement to, in rare cases, paralysis. In general, symptoms include tingling, numbness, motor weakness, radiculitis/radiculopathy, cramps, spasms, involuntary muscle twitches, and bowel, bladder, sexual problems. These symptoms may be transient or permanent. Patients with significant involvement can suffer severe disability secondary to their symptoms. Involvement largely tends to affect the lower nerve roots of the cauda equina, although reports at the cord level in the thoracic spine have been described.⁷¹⁻⁷³

The diagnosis of arachnoiditis is typically confirmed by advanced imaging including CT myelogram or MRI, which demonstrate abnormal grouping of nerve roots.^{71,74} One study grouped adherent nerve roots into three different patterns: centrally clumped, peripherally clumped (empty sac sign), or soft tissue infiltration of the arachnoid space.⁷⁴ If the appropriate constellation of symptoms is found in conjunction with these radiographic findings, a diagnosis of arachnoiditis may be made. If there are radicular symptoms, the disease may also be evaluated with EMG and its progression or remission may be followed.^{69,75}

The treatment for arachnoiditis focuses on multimodal pain relief. In addition, a multifaceted approach is often utilized that can include pain pharmacotherapy, exercise, physical therapy, and psychotherapeutic intervention. The prognosis varies depending on the severity of presenting symptoms.^{69,75}

During surgery, injury to the lumbar paraspinal muscles can occur due to muscle retraction.⁷⁶⁻⁸¹ Histologic and

biomechanical analysis of lumbar muscles following spine surgery has been performed before and after surgical retraction. Early injury is significantly correlated with retraction and operation time. Neurogenic changes have been observed for >10 months following surgery. Injury has also been directly correlated to both the duration and pressure of retraction and the extent of the exposure. Creatinine phosphokinase MM isoenzyme activity has been shown to be elevated following surgery. Longer retraction time has also been shown to result in a delay in recovery of muscle strength and a greater incidence of postoperative lower back pain. Studies show at least a 30% decrease in postoperative back strength following spine surgery at their 1-year post-op visit, suggesting a greater role for intensive physical therapy to regain physical strength.^{8,76-81}

Long-term Postoperative Factors

Long-term postoperative factors include worsening or progressive disease, scar tissue leading to epidural and peridural fibrosis, and pseudarthrosis.^{49,82} Progressive degenerative disease and degeneration of adjacent motion segments are all long-term factors causing increased pain.⁸² Following fusion, biomechanical forces are transferred to adjacent segments, increasing their risk of degeneration.⁸² Epidural fibrosis can cause recurrent radicular pain in the first 6 months following lumbar discectomy.⁸³ However, studies show conflicting findings in the relationship between scarring and postoperative pain. One study of MRIs taken at 6 months postoperatively shows that patients with greater peridural scar have a significantly greater increase in postoperative pain than patients with less peridural scarring.⁸³ However, another study shows no correlation between MRI findings of increased epidural scarring and recurrent postoperative pain.⁸⁴

Failure due to pseudarthrosis can be a significant cause of continued pain in the long-term following a spinal fusion.⁸⁵ This usually results in the return of both axial and radicular pain within the first year following surgery.⁸⁵ Risk factors include preoperative disc height, slip angle and segmental kyphosis.⁸⁶ Disc height >20% difference or with segmental kyphosis demonstrated an increased risk of pseudoarthrosis.⁸⁶ Anteroposterior and lateral radiographs can demonstrate typical findings of pseudarthrosis.⁸⁷ These include resorption of bone graft in the lateral gutters at 12 weeks, fatigue failure of posterior instrumentation,

radiolucencies around pedicle screws, or gaps between interbody graft or cages and vertebral endplates.⁸⁷ This can be identified through CT, plain radiographs including flexion and extension films.⁸⁵ Computed tomography and single photon emission computed tomography (SPECT) with CT can be used to identify screw loosening, nonunion around cages, and facet joint degeneration.⁸⁸ An SPECT with CT can also be used to improve the identification of nonunion and facet joint degeneration.⁸⁸ Surgical exploration is the gold standard for spinal nonunion.⁸⁷

PATIENT EVALUATION WITH FAILED BACK SYNDROME

Patient evaluation begins with a thorough history from the patient. It is important to understand the relation between preoperative and postoperative pain and any similarities and differences. In addition, timing of pain—i.e. whether immediate onset, subacute onset or onset of pain following a long period of relief—following lumbar surgery should be clarified. It is imperative to review the patient's past medical history and social history to rule out other diagnoses and to evaluate the patient for treatable patient factors and comorbidities (e.g. depression, substance abuse, workforce status, somatization, secondary gain, workman's compensation, and litigation). Psychosocial factors should be addressed prior to undergoing revision surgery. In addition, a thorough review of systems should be performed to rule out any other pathology, including infection or tumor.⁷

Physicians treating patients with continued chronic pain following lumbar surgery should have a low threshold for referral to psychologist or psychiatrist. Chronic pain and disability can worsen previous psychological comorbidities⁷ and psychological comorbidities can also worsen pain symptoms. Structured interviews and formal testing, such as the MMPI (Mean Minnesota Multiphasic Personality Inventory), are part of psychological workup for patients with psychological comorbidities or risk factors for psychiatric disorders. It is strongly predictive of surgical prognosis for patients with chronic pain.⁸⁹ However, one cannot rule out anatomic pathology based on psychological screening.

Physical Examination

The physical examination of a patient with FBS is similar to the preoperative patient evaluation. The examiner should

rule out Waddell signs.⁹⁰ These include superficial and nonanatomic tenderness, pain with axial compression or simulated rotation of the spine, negative straight-leg raise with patient distraction, regional disturbances that do not follow a dermatomal pattern, and overreaction to physical examination. In addition, a patient's gait, location of tenderness to palpation, joint range of motion (hip, knee, ankles), strength, sensation, peripheral pulses, upper motor neuron signs, and long tract signs can help evaluate and differentiate intraspinal from extraspinal sources of pain.⁷

Imaging

Imaging of the patient should include a review of available preoperative, intraoperative, and postoperative imaging. Radiographs should be used to evaluate spinal alignment and hardware loosening, subsidence, displacement, or breakage, and evidence of disease progression. Full-length standing radiographs should be obtained to evaluate sagittal alignment and the C7 plumb line. Dynamic radiographs can help evaluate for instability. Radiographs of other lower extremity joints can rule out concomitant orthopedic pathology.⁷ Magnetic resonance imaging with and without gadolinium is more effective for the postoperative spine than noncontrast MRI alone.^{7,91} It has up to 96% accuracy in differentiating epidural scar from disc material, including a recurrent disc herniation.⁹¹ Signal-intensity changes with epidural scar compared with disc material are subtle on T2-weighted images without contrast because disc material can be contiguous with the disc space. Following injection of contrast, scar enhancement is intense compared to disc material allowing for better delineation of scar from disc material. The addition of gadolinium can also help identify postoperative infection. It can help identify an epidural abscess and differentiate it from an adjacent compressed thecal sac. In addition, gadolinium can help to localize a paraspinal mass for a percutaneous biopsy and to identify an active infection.⁹²

The CT myelography is a valuable resource, especially when MRI is contraindicated with stainless steel instrumentation, with dynamic problems, and with scoliosis to better delineate the bony anatomy. Stainless steel instrumentation produces signal distortion and artifact that can compromise MRI clarity.⁹³ Plain CT is helpful for evaluation for pseudoarthrosis in combination with flexion/extension radiographs.⁹⁴ However, these imaging

studies still may not correlate with surgical findings⁹⁴ and radiographs may underestimate the fusion.⁹⁵

Electrodiagnostic studies including electromyograms (EMG) and nerve conduction velocity (NCV) are helpful in evaluating nerve root compression and locations of injury. They are useful in differentiating extraspinal impingement and pathology from intraspinal pathology and give an objective measure of nerve compression in patients with chronic pain.⁷

Laboratory evaluation can aid in workup for infectious. It should follow a thorough history and physical examination evaluating for constitutional symptoms. Patients usually note a different quality of pain after discectomy, which is an early symptom of diskitis. Erythrocyte sedimentation rate (ESR) and C-reactive protein (CRP) are the mainstays of laboratory evaluation. Although they are nonspecific, CRP peaks 2–3 days after spine surgery with rapid fall within 4–6 days and usually returns to normal by 14 days,⁹⁶ sooner than ESR.

Selective nerve root and facet joint blocks are helpful in localizing the source of the pain and can be both diagnostic and therapeutic. They are a safe and minimally invasive adjunct to a thorough evaluation. However, evidence is lacking in the effectiveness in the utility of joint blocks in assessing prognosis of repeat surgery.^{97,98} In addition, they usually provide only a temporary relief of pain and do not offer long-term pain relief.

Discography is extremely controversial. Provocative discography is an invasive diagnostic tool and should be used only for carefully selected patients after a thorough history, physical examination, and imaging. It consists of injection of contrast into the nucleus pulposus. It allows for assessment of disc morphology as well as patient response to pain provocation.^{99,100} A recent study demonstrated that lumbar discography had a negative effect on the discs tested.¹⁰¹ Discography resulted in a progression of degenerative changes, increased risk of disc herniations at the site of injection of contrast, loss of disc height and signal intensity, and increase in reactive endplate changes at 10 years postdiscography.¹⁰¹

TREATMENT OPTIONS

Nonoperative Treatment

Treatment of FBSS usually begins with nonoperative management. These include physical therapy, behavioral therapy, and specialized pain management. Neuropathic

pain can be treated by a wide variety of oral medications, including anti-inflammatory medications, tricyclic antidepressants, and anticonvulsants. In addition, physiotherapy, chiropractic therapy, acupuncture, muscle relaxation, and behavior modifications have been shown to be useful.¹⁰²

Interventional Pain Management

Interventional pain management options include adhesiolysis and epidural injections, medial branch blocks, and spinal cord stimulation. Epidural steroid injections (ESIs) are considered in patients who have failed to respond to less invasive treatment and prior to considering more invasive treatments.¹⁰³ Epidural steroid injections can be utilized for both diagnostic and therapeutic effects.² They have been shown to result in significant improvement in the visual analog pain scale at 3 weeks and 6 months. Success was defined as a 50% decrease in VAS score. The success rate was 84% at 3 weeks and 78% at 6 months. Epidural steroid injections significantly decreased the intensity of low back pain with FBSS.¹⁰⁴ A randomized controlled trial comparing injections of steroid to local anesthetic into the epidural space demonstrated that 60% of patients achieved >50% pain relief and disability reduction over 1 year with steroids.¹⁰⁵⁻¹⁰⁷ Improvements of these patients averaged 75% with an average of four procedures per year.¹⁰⁵⁻¹⁰⁷ Transforaminal steroid injection has also been shown to be effective for radicular pain following discectomy.¹⁰⁸ However, it has been shown to be effective in only 25% of patients with persistent radicular symptoms.¹⁰⁸ Most notably, however, it has been shown to result in significant pain relief in up to 43% of patients without a recurrent disc herniation.¹⁰⁸

Following spinal surgery, adhesions can form in the epidural space resulting in scarring and perineural fibrosis. The scar tissue can cause compression, inflammation, swelling, or decreased nutritional supply with resultant nerve root hypersensitivity.^{109,110} This can prevent steroid injections from travelling to their desired locations.¹¹¹ Spinal adhesiolysis, including percutaneous or endoscopic, is an option to treat epidural adhesions. It can be used to treat pain due to scarring.¹⁰⁹ Adhesiolysis can be mechanical with a wire-bound catheter or with placement of a catheter in the epidural space and infusion of high volumes of anesthetics, hypertonic or isotonic saline, and steroids.¹⁰⁹ Infusion of hyaluronidase can reduce the fibrosis.¹¹⁰ A recent systemic review demonstrated fair evidence that percutaneous adhesiolysis can be used to

relieve low back and leg pain for FBSS. The incidence of complications is low and usually self-limited.¹⁰⁹

Spinal adhesiolysis can be supplemented with epidural injections, allowing dispersal of corticosteroids throughout the prior surgical area. Epidural steroids with percutaneous adhesiolysis demonstrated a significant improvement in postoperative low back and leg pain and functional status over ESI alone.^{103,112} Studies have shown up to 50% pain relief, functional improvement, improvement of psychological status, and return to work. In addition, studies have shown strong evidence for short-term relief (i.e. <3 months), and moderate evidence for long-term relief.¹¹³⁻¹¹⁵ Direct medication administration via an intrathecal drug pump has also been shown to be helpful in reducing chronic or recurrent pain following spinal surgery. Although associated with high initial costs, it has been shown to be cost-effective if used for >12 months when compared with conventional therapies.^{102,116} Epidural steroid injection with and without adhesiolysis has been shown to offer short-term pain relief, but adhesiolysis significantly improved long-term pain relief in patients with FBSS.¹¹⁰ Another randomized trial comparing ESI combined with percutaneous adhesiolysis versus ESI alone demonstrated significant pain relief and functional status improvement in the disability score in 73% of patients with percutaneous adhesiolysis as opposed to only 12% with traditional ESI.¹⁰⁶ Average total relief was 42 out of 52 weeks with percutaneous adhesiolysis versus only 13 weeks for ESI alone.¹⁰⁶

Zygapophysial joint pain is an uncommon occurrence following lumbar surgery, specifically in discectomy.¹¹⁷ It can be a source of pain following lumbar surgery.¹¹⁷ Diagnostic and temporary treatment can be achieved through repeated medial branch blocks.¹¹⁷ Radiofrequency neurotomy has been shown to achieve significant pain reduction in these patients as well.¹¹⁷

Spinal cord stimulation (SCS) has been in use for >30 years and is used usually for neuropathic pain in the treatment of nociceptive pain.¹¹⁸ Spinal cord stimulation involves placement of percutaneous leads or electrodes in the epidural or intrathecal space with production of electrical stimulation by pulse generator over the spinal cord based on the patient's pain.¹ Spinal cord stimulation is postulated to work through the gate-control theory—through inhibition of transmission of nociceptive signals.¹¹⁸ It is related to the release of gamma-aminobutyric acid (GABA)-ergic and adenosine-related mechanisms in segmental spinal levels. Spinal cord stimulation reduces the

release of excitatory amino acids (glutamate, aspartate), and GABA release is augmented.¹¹⁸ However, most studies have been done on animals, and therefore there are no human studies regarding the mechanism of spinal cord stimulation on humans due to the complexity of its mechanism of action.¹¹⁸ A recent randomized controlled multicenter trial (PROCESS) trial of 100 patients compared medical management to spinal cord stimulation.¹¹⁹ Medical management included nonsteroidal anti-inflammatory medications, narcotics, antidepressants, and anticonvulsants/antiepileptics, nerve blocks, epidural steroid injections, physical and psychological rehabilitation, and chiropractic care. Spinal cord stimulation demonstrated improvement in leg pain, quality of life, and functional capacity, although 13 of the 42 patients treated with spinal cord stimulation required surgical revision.

Complications of spinal cord stimulation include electrode migration, loss of paresthesia, pain at implanted pulse generator incision site, infection or wound breakdown.¹¹⁹ Other complications include infection, lead migration, breakage, CSF leak and weakness.¹ In total, 31% (13) required surgical revision, the majority of which were in the first year,¹¹⁹ and 89% of patients were satisfied with SCS at 2 years.¹¹⁹ Another study demonstrated that permanent electrode placement resulted in at least 50% relief with reduced opiate analgesic requirement and was more effective than surgery.¹²⁰ However, those patients with objective anatomic surgical pathology, including neurologic deficit caused by surgical remediable compression, cauda equina compression, or gross instability requiring surgery, were excluded from the study.¹²⁰ A meta-analysis of 74 studies demonstrated a mean pain relief of 58% at 2 years follow-up. No predictive patient or technological factors were identified.¹²¹ Improvement in pain at longer-term follow-up has also been demonstrated. At 8.3 years, 75% of patients in one study demonstrated low back pain relief of >50%. Activities of daily living increased including ability to sit, climb stairs, and walk of >75%. Drug consumption decreased by >50% in 66% of the patients.¹²² Another study on 707 patients who received SCS therapy found no patient with permanent neurological deficits or deaths. Complications included lead migration (22.6%), lead connection failure (9.5%) and lead breakage (6%) requiring revision or replacement. Pain at the generator site (12%) and clinical infections (4.5%) were also noted. Patients with diabetes had an infection rate of 9% and those without diabetes had an infection

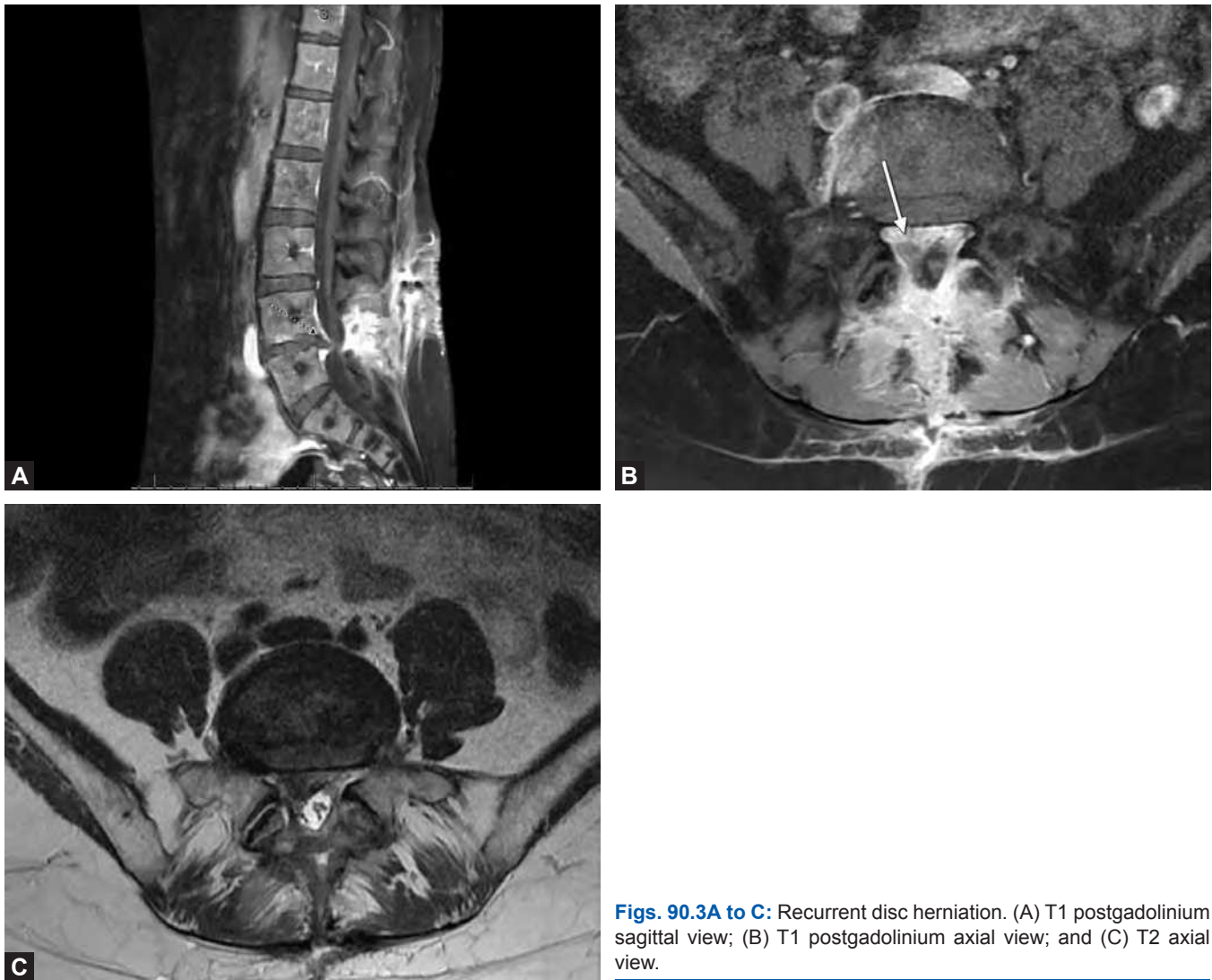
rate of 4%. Infections were treated with explanation and antibiotic therapy with no permanent complications.¹²³

Surgical Intervention

It is important to evaluate the patients for surgically correctable pathology as either the cause of their back pain or of their leg pain. Multiple pathologies may be evident on imaging, and therefore it is imperative to correlate diagnostic imaging findings with the patient's history and physical examination.² Flexion and extension radiographs, MRI with and without contrast, and CT myelograms are important tools in identifying possible pathology, including continued stenosis, recurrent disc herniations, instability, malignancy, and postsurgical complications including infection.² Results from revision surgery are poorer than the index procedure. Most patients who are deemed surgical candidates should have other diagnoses not related to the spine ruled out as their source of pain and should have failed extensive nonoperative treatment or have had only temporary relief from nonoperative interventions.⁷

Recurrent and residual spinal stenosis, most commonly foraminal stenosis, following lumbar surgery can be due to inadequate decompression, recurrent disc herniation, instability, scar formation, or adjacent level disease.¹²⁴⁻¹²⁶ Patients with recurrent stenosis demonstrate an increase in duration of symptoms and significantly less improvement in disability due to low back pain.¹²⁴ Reoperation for adjacent level disease was equal to reoperation at the index level.¹²⁴ No difference was seen between instrumentation, spinal canal diameter, or multilevel laminectomy between those patients who underwent reoperation and those who did not.¹²⁴ Moderate and marked regrowth demonstrates significantly decreased satisfaction, and is generally greater in those patients who do not undergo an arthrodesis procedure.¹²⁷ Recurrent lumbar stenosis has shown a significant improvement after revision lumbar surgery with improvement in low back pain, disability, and quality of life.¹²⁸

Recurrent disc herniation (Figs. 90.3A to C) as a cause of recurrent stenosis can result in significant leg pain and poor outcome following lumbar discectomy. Asymptomatic recurrent disc herniations have been shown in up to 25% of patients within the first 2 years.¹²⁹ However, the incidence of symptomatic recurrent disc herniations ranges from 5% to 15% and results in a significant increase in leg pain and disability.¹²⁹⁻¹³¹ Disc height loss was not seen in either symptomatic or asymptomatic recurrent



Figs. 90.3A to C: Recurrent disc herniation. (A) T1 postgadolinium sagittal view; (B) T1 postgadolinium axial view; and (C) T2 axial view.

disc herniations.¹²⁹ Risk factors for recurrent herniation include preoperative size and level of the disc herniation, male gender, a history of smoking, tall height and obesity, younger age, occupational repetitive lifting or vibration, and heaving lifting.¹³⁰⁻¹³³ Repeat discectomy should be considered only if the patient's radicular symptoms and physical examination findings correlate with radiographic imaging. Repeat discectomy for a recurrent disc herniation has been shown to require a significantly longer operating time.^{131,132} However, significant improvement and results similar to primary discectomy have been demonstrated with significant improvement in leg pain, quality of life similar to primary discectomy with no significant difference in hospital stay or postoperative clinical course. In

addition, age, gender, smoking, profession, and level of herniation did not affect clinical outcomes.^{131,132,134}

Instability, including postoperative spondylolisthesis or postoperative scoliosis following discectomy, laminotomy or lumbar decompressive laminectomy, has been shown to have an association with instability, most notably with significant resection of the facet joints (*see* Figs. 90.1A and B). Multilevel discectomies and foraminotomies also have been shown to result in increased sagittal motion.^{135,136} Significant resection of the spinous process, interspinous ligaments, and supraspinous ligaments during decompression increases the risk of segmental instability.¹³⁷ The posterior ligamentous complex acts as a tension band to stabilize the spine and can be lost during the index

lumbar surgery.¹³⁷ Preoperative indicators for instability included degenerative disc with radiographic changes, including traction spurs and loss of disc height, listhesis, and scoliosis.¹³⁸⁻¹⁴¹ Selective facetectomy is important in lumbar decompression and does not compromise the stability of the motion segment.⁴² However, total facetectomy and excision of the pars interarticularis result in spinal instability.^{42,138-140} The posterior elements should be spared as much as possible to avoid instability.¹³⁸ Symptoms include worsening back pain, radicular pain, increased motor weakness and sensory deficits.¹⁴² Radiographic changes include loss of disc height >30%, or spondylolisthesis on dynamic radiographs of >3 mm.^{142,143} Treatment involves reoperation with spinal fusion with or without secondary laminectomy.^{138,142} Significant improvement in postoperative pain was noted; however, improvement in motor and sensory symptoms was seen only in 50% of patients.¹⁴²

Flatback syndrome can result in significant postoperative morbidity (Figs. 90.2A and B). The goal is to restore sagittal alignment and recreate lumbar lordosis following lumbar spinal surgery.¹⁴⁴ Bracing alone has been shown to be ineffective in treating flatback syndrome.¹⁴⁵ In addition, surgical arthrodesis with no sagittal correction has poor long-term success.¹⁴⁴ Multiple corrective osteotomies can be used to correct sagittal imbalance. These include Ponte osteotomy, Smith-Peterson osteotomy, pedicle subtraction osteotomy, and vertebral column resection. These typically allow for shortening of the spine. Ponte and Smith-Peterson osteotomies allow up to 10° of kyphosis correction per level. A pedicle subtraction osteotomy allows for 30–40° of angular correction and is generally done at the site of maximum deformity. Vertebral column resection results in complete discontinuity of the proximal and distal aspect of the spine, allowing for >60% local sagittal and coronal plane correction.^{47,146-148} Flexible kyphosis following multilevel laminectomies can be treated with spinal arthrodesis alone.¹⁴⁵ Patient with severe and stiff kyphosis can be treated with corrective osteotomy and spinal arthrodesis.¹⁴⁵

Pseudoarthrosis following lumbar surgery can be treated with iliac crest autograft and pedicle screw instrumentation. Revision surgery demonstrates a high rate of solid fusion, but did not always correlate with improved clinical outcomes and has variable outcomes depending on the diagnosis.¹⁴⁹ In patients with degenerative disc disease, revision surgery demonstrates only a 50% improvement in their symptoms. In patients with

spondylolisthesis, however, revision surgery demonstrates a 64% improvement in their postoperative ODI scores following successful repair of their nonunion.¹⁵⁰ Revision lumbar arthrodesis for symptomatic pseudoarthrosis can improve low back pain, disability, and quality of life.¹⁵¹ Improvement continued to be noted at 2 years following revision surgery.¹⁵¹ Patients were independent of narcotics on average at 12 months postoperatively and return to work was 4 months postoperatively. No patient had repeat pseudoarthrosis at 2 years.¹⁵¹ However, no significant improvement was noted in the mental component score or self-rating depression scale score and it was noted that mental health symptoms may be more refractory to revision surgery.¹⁵¹

Overall, visual analog scores for back pain and Oswestry Disability Index were improved significantly with revision decompression and instrumented fusion for adjacent segment disease, pseudoarthrosis and recurrent stenosis.¹²⁸ Revision surgery for these diagnoses resulted in significant improvement in low back pain, disability, and quality of life.¹²⁸ They further evaluated the cost-effectiveness of revision surgery for these diagnoses and found a mean 2-year cost of \$80,594 per quality-adjusted life year.¹⁵²

Occasionally patients may note significant back pain despite any evidence of pathologic findings on history, physical examination, or radiographic findings and with evidence of a solid fusion. Patients with tenderness to palpation along the hardware can undergo anesthetic injections along the hardware at the sites of greatest pain.¹⁵³ Significant pain relief following anesthetic injection has been shown to be a predictor of significant pain relief following implant removal.¹⁵³ A significant decrease in pain was noted in these patients following implant removal with only a small incidence of complications.¹⁵⁴ Although a majority of patients note significant pain relief and would repeat the removal of hardware operation, only 12% in one study noted complete pain relief.¹⁵⁴ In addition, patients should be followed for worsening of their deformity following implant removal.¹⁵⁵ A significant number of patients initially treated with scoliosis had worsening of their coronal curve and a more frequent worsening of their sagittal curve following implant removal.¹⁵⁵ This was more common in patients with a larger preoperative sagittal kyphosis and did not correlate with the reason for implant removal or postoperative time between the initial surgery and the implant removal.¹⁵⁵

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SECTION

9

Motion Preservation

Alexander R Vaccaro



Biomechanics of Motion Preservation Strategies

Hans-Joachim Wilke

Snapshot

» Posterior Implants

» Anterior Implants

INTRODUCTION

For many years, the “Golden Standard” in spinal surgery in order to treat different spinal pathologies, such as fractures, instabilities or degeneration, was to fuse motion segments by bridging the treated segment with stiff implants. The goal was to stabilize the spine as good as possible to allow fast bony fusion, on the basis of the maxim “the stiffer the better”. In many patients, the outcome of these surgical interventions was quite good; however, in some cases, degeneration in the adjacent segments was observed.^{1,2} Although it is still not proven,^{3,4} it was quickly hypothesized that the fusion is responsible for this so-called “adjacent level syndrome” because the stiff region in the spine leads to an overload in the segments above and below.⁵

Particularly in the last decade, nonfusion technologies in spinal surgery have gained more and more popularity.⁶ Constantly new ideas are created and turned into new products. Each idea has its own philosophy with the principle goal to restore and maintain the disc height and/or original mobility of a healthy segment. Furthermore, these ideas allow preserving at least partially some spinal structures, which are sacrificed with spinal fusion.

These motion preservation strategies have led to different implant categories, which can be divided into posterior or anterior devices (Fig. 91.1).

- The goal of posterior devices is to stabilize the treated segments but preserve the disc or just to unload or to replace the facet joints. The most important represent-

atives are flexible stabilization systems such as dynamic fixators, interspinous implants that are just placed between the spinous processes or implants to replace the facet joint or the entire posterior complex.

- The anterior technologies are total disc prostheses, nucleus replacement devices or ideas to seal or close a hole in the annulus.

POSTERIOR IMPLANTS

Dynamic Stabilization Systems

Internal fixators are generally used to stabilize a degenerated segment and to promote fusion, after the disks are replaced either by intervertebral cages, allografts or autologous bone grafts. However, from a clinical point of view it may not be desirable to sacrifice a moderately degenerated disc and to cause donor site morbidity for the use of autologous bone grafts.

Therefore, already in 1992 the so-called ligamentoplasty was suggested, a technique in which the pedicle screws were tightened with polyester ring bands.⁷ With this technique, it was possible to maintain the disc and the physiological lordosis in the lumbar spine. It was shown that the instability, which is created by a laminectomy and the partial removal of the facet joints, could be reduced in all directions with this technique.^{8,9}

A few years later, the first dynamic fixators were introduced, which connect the screws with flexible longitudinal elements instead of rigid rods (Figs. 91.2A and B).

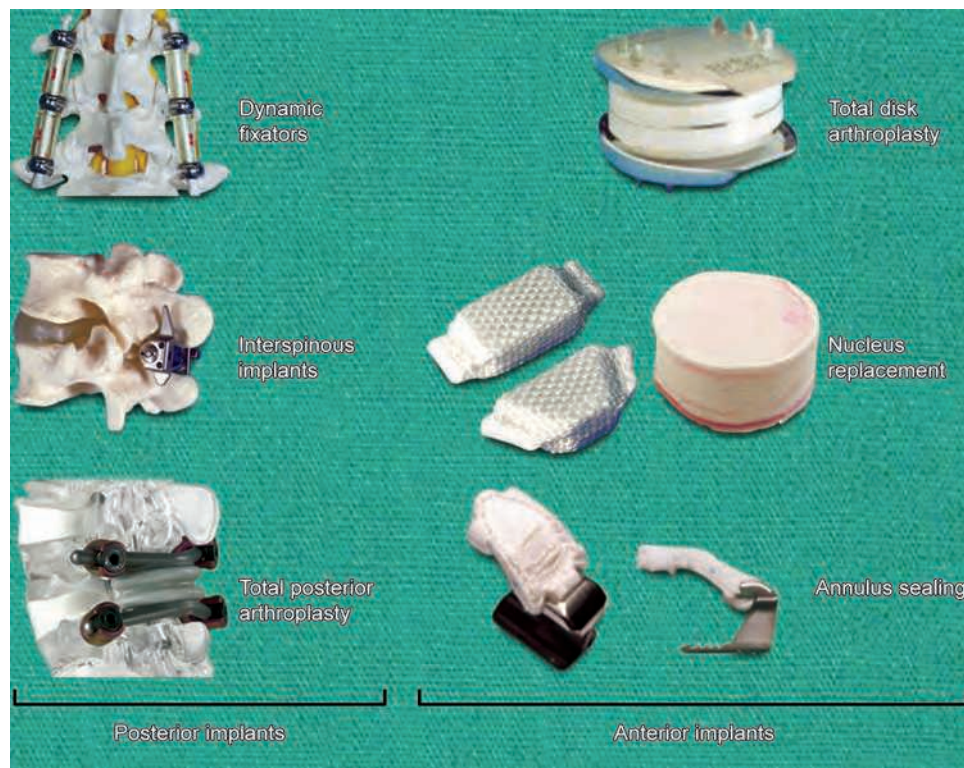


Fig. 91.1: Representative pioneering implants of the different categories for motion-preserving technologies in spinal surgery.

The first clinically used implant of this type was the Dynesys Spinal System (Centerpulse Orthopedics Ltd, Winterthur, Switzerland) to provide spinal alignment and dynamic restabilization up to five contiguous levels from L1 to S1 while preserving the disc as well as the facet joints (Dynamic Neutralization).¹⁰⁻¹² It is composed of pedicle screws, polyethylene terephthalate cords and polycarbonate urethane spacers. The spacers are placed bilaterally between the pedicle screw heads to withstand compressive loads. The cords are running through the hollow core of the spacers and stabilize the construct by a tensile preload.

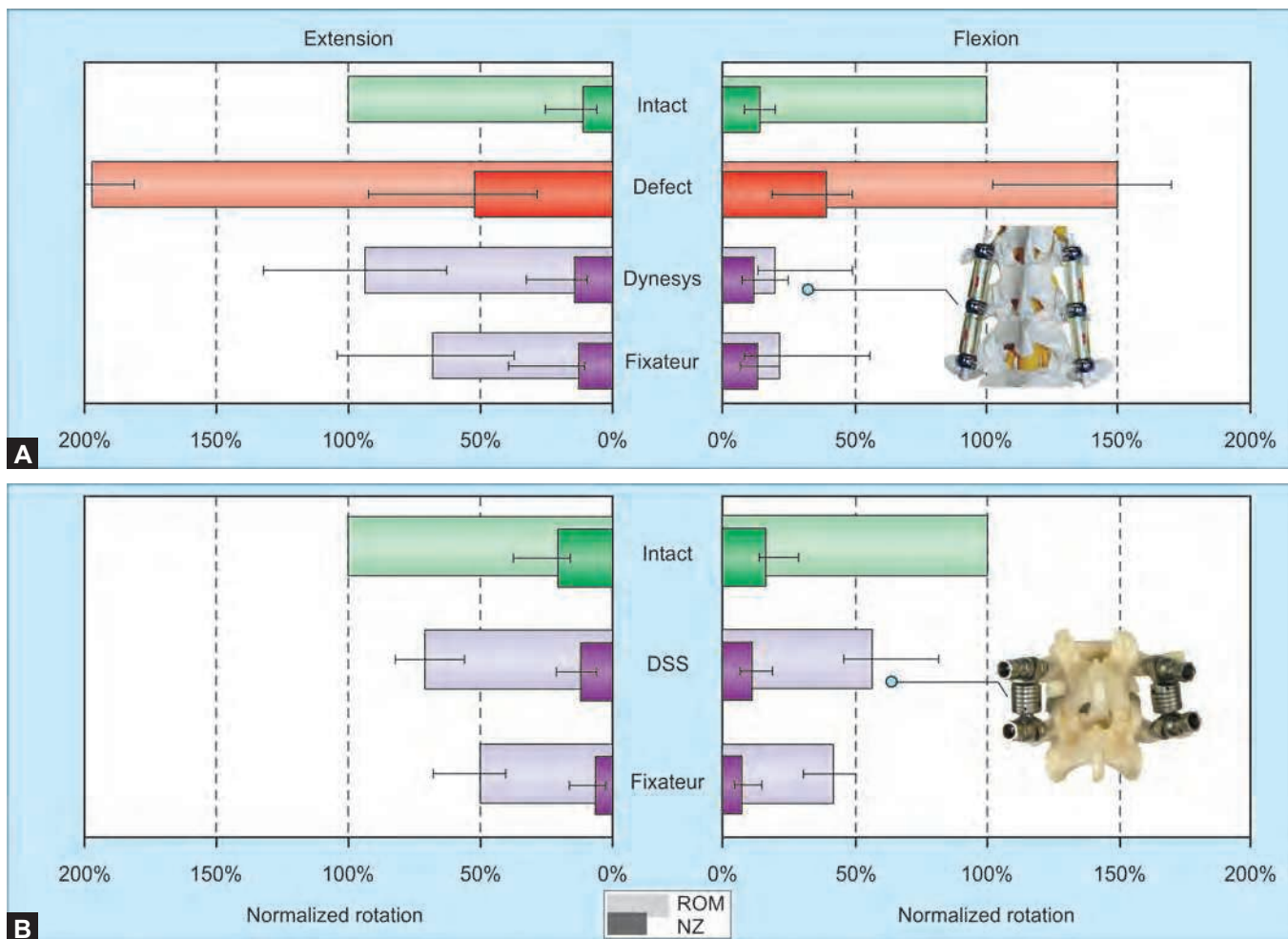
Our own biomechanical in vitro investigations have shown that a segment with a large defect could be stabilized again with the implants in most directions (Figs. 91.3A to F).^{13,14} The Dynesys stabilized the spine significantly but was only slightly more flexible than the internal fixator, most pronounced in extension. In flexion, however, the Dynesys provided the same stiffness as the internal fixator, because both rods act as tension band posteriorly of the spine. In axial rotation, there was a big difference between both implants. The internal fixator was able to restore the normal range of motion, whereas the Dynesys allowed for larger motions, which were even above the normal values of intact segments. If

the spacers are too long, the Dynesys acts to distract the facet joints; that is, the range of motion in axial rotation increases with greater spacer length.¹⁵

As this concept of dynamic stabilization *per se* was considered as superior to former implants and widely accepted, a large number of implants followed and are still in the development phase.^{16,17} They allow more flexibility but at the same time control the stability of the motion segment through joints, springs, or complex spring-damping systems (Fig. 91.3).¹⁸ The problem is that it is still not known how much flexibility or stability is optimal for these kinds of implants.

Interspinous Implants

Interspinous implants are placed as spacers between the interspinous processes. The goal is to unload the facet joints and the disk, to restore foraminal height and to provide sufficient stability, especially in extension, but still allow motion in the treated segment. They are primarily used for posterior lumbar spinal pathologies such as spinal stenosis or facet joint arthritis, although the indications are not yet clearly defined because scientific evidence is still lacking (Figs. 91.4A to D).^{19,20}

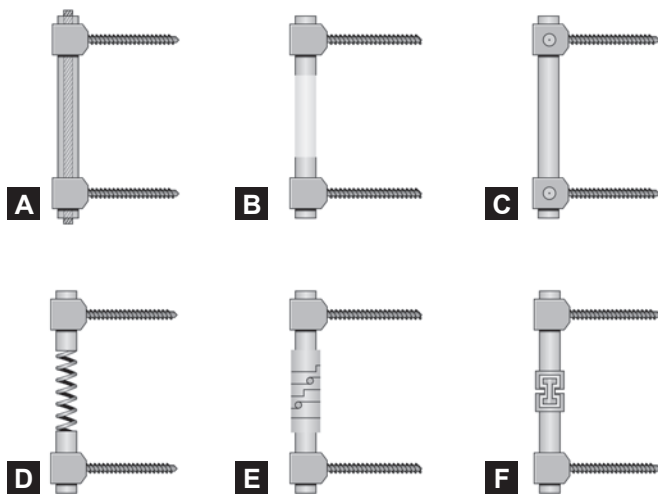


Figs. 91.2A and B: Results of range of motion (ROM) and neutral zone (NZ) in flexion and extension normalized to the intact state. The test of the upper diagram was performed with six L3–4 segments with a defect (dissection of the supraspinous ligament, interspinous ligament, flavum 1, tenotomy of facet joint capsules and a nucleotomy).^{13,14} The test in the lower diagram was performed with six L2–3 segments without a defect.

Because the implantation is simple and has only a low risk for the patient, this technology became quickly very popular. More and more interspinous implants appeared on the market. Some of these implants are, e.g. pierced through the interspinous ligament to preserve the supraspinal ligament and secured in place with two lateral wings or with ligatures around the processes. Other implant variations require cutting the supraspinous ligament to enable the placement of the implant. To compensate for the putative function of the sacrificed ligaments, these implants are usually fixed with bands or cords on the spinous processes or the wings are crimped to the spinous processes.

Most spacers mainly prevent spinal extension and unload the disk, but at the same time allow physiological movement in all other directions. U-shaped implants

may provide an additional damping effect due to the deformation of their spring-like shape and their mobile center of rotation during motion. Our own biomechanical in vitro experiments have shown that four evaluated interspinous implants had a similar effect on the three-dimensional flexibility of the treated segments.²¹ They significantly stabilized the unstable segment in extension and restricted the range of motion to about half of that of the intact state and unloaded the disc (Fig. 91.5). In the other planes, however, especially in lateral bending and axial rotation, the values of range of motion did not significantly change compared to the values of the destabilized state. Similarly, the load on the disc was decreased significantly with all implants during extension but not in flexion, lateral bending and axial rotation.

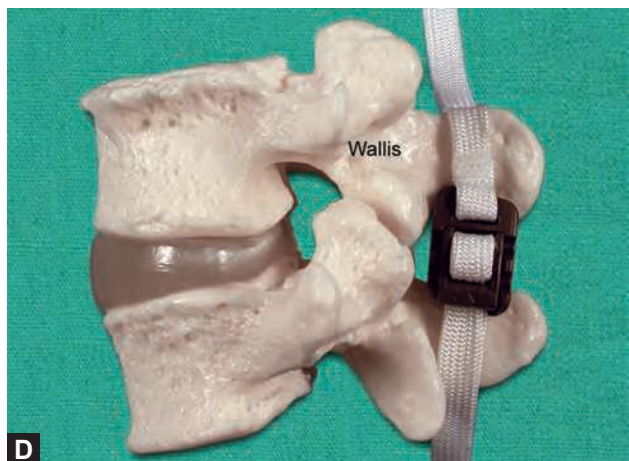
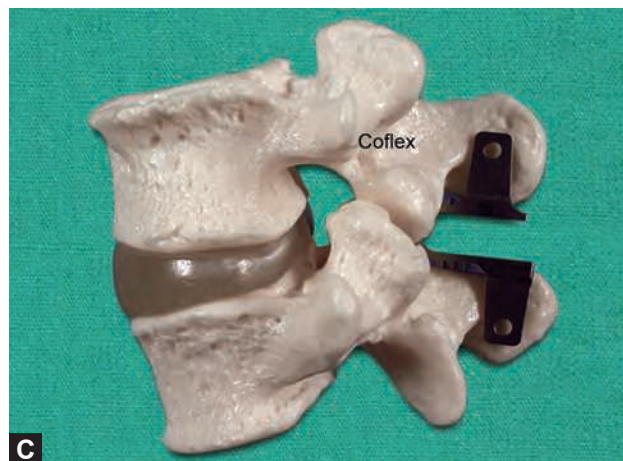
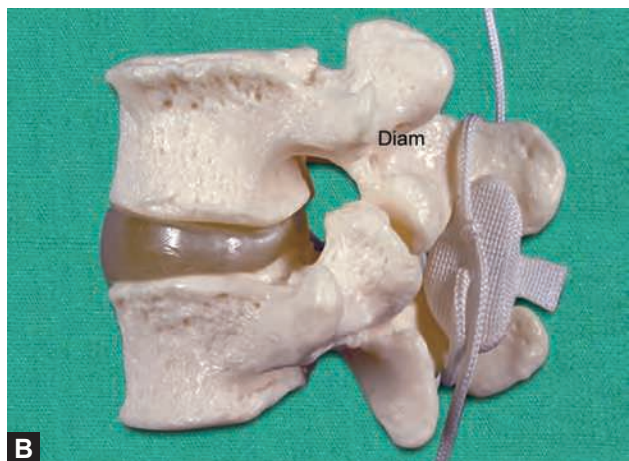
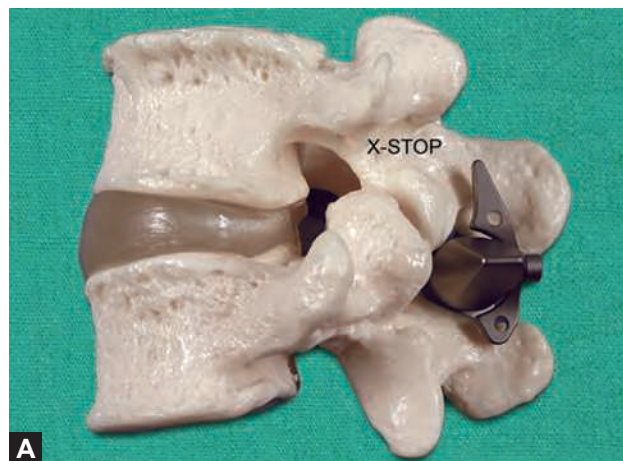


Figs. 91.3A to F: Different principles for dynamic or semirigid fixators or couplers that are in clinical use: (A) Polycarbonate urethane spacers and polyethylene terephthalate cords; (B) elastic elements in the rods; (C) screw fixations with hinge-joints; (D) spring elements; (E) complex spring-like elements; and (F) spring-damper systems.

Total Posterior Element Replacement System

Facet joint arthritis can occur independently of disc degeneration. Therefore, there are implants that replace the entire posterior complex of a spinal segment or only the articular facets.²² Most systems are fixed with four transpedicular screws. Experimental investigations have shown that some implants may mimic almost the ideal range of motion in flexion, extension, and lateral bending. The geometry of the implant is even able to control the physiological range of motion in axial rotation with respect to posture, i.e. more in flexion and reduced motion in extension.²³

New implant ideas even try to only replace the articular surfaces of the small joints. These small implants are anchored with pins in the joints. However, little is known about such approaches so far. Before they can be used in clinical application, experimental studies must prove that these implants permit the desired movement, guarantee



Figs. 91.4A to D: Interspinous implants.

in the long term a reliable fixation, and that only a slight abrasion occurs.

All posterior devices maintain motion and some loading of the disk. It may be assumed that physiological loading of the disk has advantages to the disc structures and its regenerative potential. This physiological loading may be expressed by the bulging of the disk. In a study using a three-dimensional laser scanning device,^{24,25} it could be shown that the more dynamic a posterior stabilization device is, the closer the disc behaves biomechanically with

the disc in a healthy segment (Fig. 91.6). The value of these differences, however, still has to be discussed with caution.

ANTERIOR IMPLANTS

Total Disc Prostheses

Total disc arthroplasty (TDA) has evolved to an extremely exciting technology over the last decade.²⁶ After the initial enthusiasm, some disillusion has also spread, because the long-term results are not as good and reliable as hoped, and it has become evident that the development of an artificial disc is a big challenge.²⁷⁻²⁹ Nevertheless, the number of disc prosthesis products on the market has grown rapidly in the recent years. Until now, many proposed solutions were fairly simple, compared to a real intervertebral disk, which has a very complex structure.³⁰⁻³² Most of the current designs are based on an articulating ball-and-socket concept, reminiscent of the conventional implant systems that were popular for small joint replacement. The various prosthesis designs attempt to control the movement directly by the geometry of the articulating surfaces, to mimic the physiological center of rotation with constrained implants or to allow a fully unconstrained motion of the individual prosthesis components in devices with mobile cores (Figs. 91.7A to D). The current trend for disc implants is to design them in such a way that the three-dimensional physiological stiffness of the natural disc is reproduced. Therefore, the

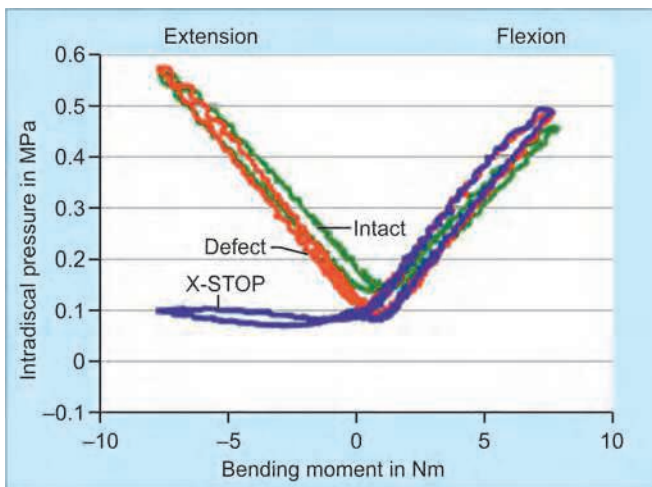


Fig. 91.5: Interspinous implants restrict motion and unload the disc in extension.

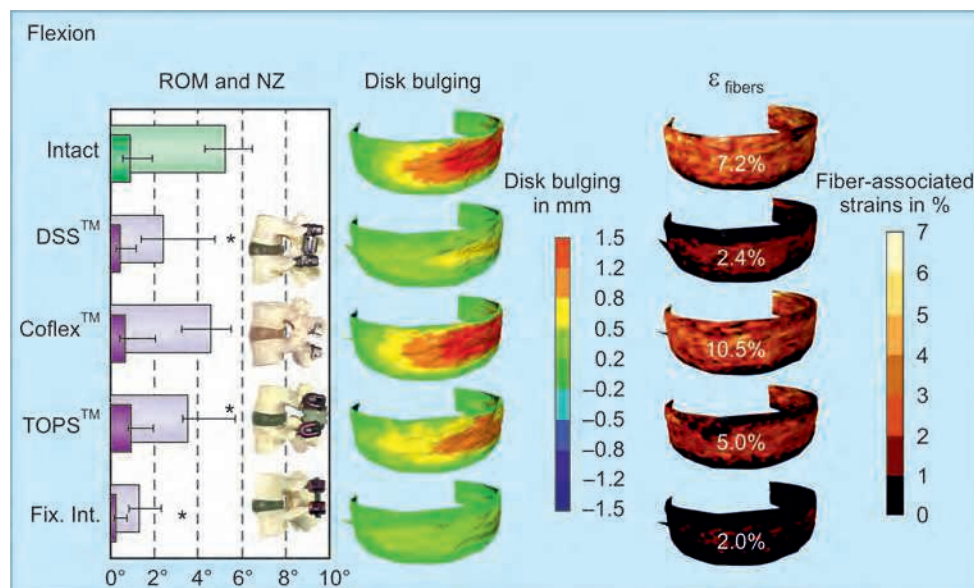
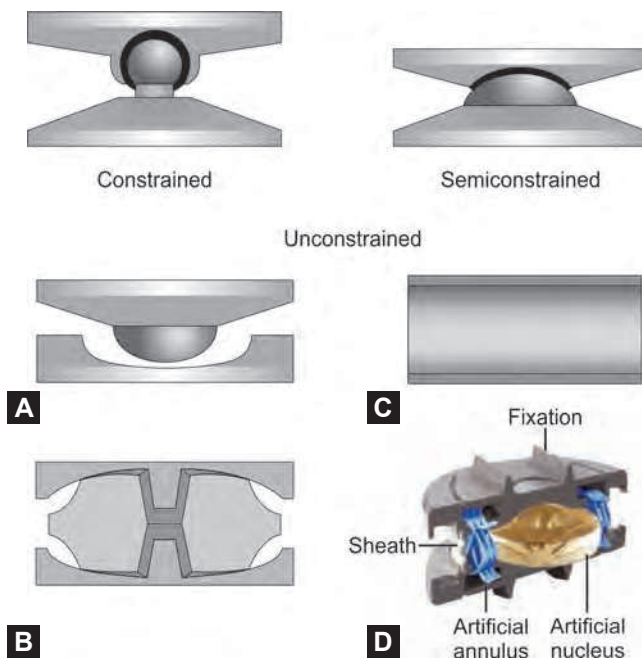


Fig. 91.6: All posterior devices allow more motion than the internal fixator and thus restore more loading on the disk, which is also expressed in larger strain in the annulus fibers.



Figs. 91.7A to D: Classification of total disc prostheses: (1) completely controlled kinematic (constrained), (2) partially controlled kinematic (semiconstrained), (3) no control through implant, i.e. all 6° of freedom possible (unconstrained). (A) Noncongruent gliding surfaces; (B) Two different pairs of gliding surfaces; (C) Deformable core; and (D) Simulation the physiological structure.

types of prostheses that are currently available can be categorized into implants with a fixed center of rotation, implants that are incompressible with a mobile center of rotation, and compressible implants with a mobile center of rotation.^{6,31,33-36}

In our *in vitro* studies, a finite element calculation simulating the influence of different design philosophies on cervical implant performance was compared. Overall, it can be summarized that unconstrained prostheses increase segmental lordosis more than semiconstrained ones.³⁷ Resection of the posterior longitudinal ligament further exaggerates this increase; however, its effect can be avoided by using a taller implant.³⁸ The prosthesis height seems more crucial than the preservation of the posterior ligament in terms of stability. The location of the center of rotation in a semiconstrained prosthesis did not alter the magnitude of range of motion. This, however, cannot be extrapolated to a change in implant position, which probably has a strong influence.

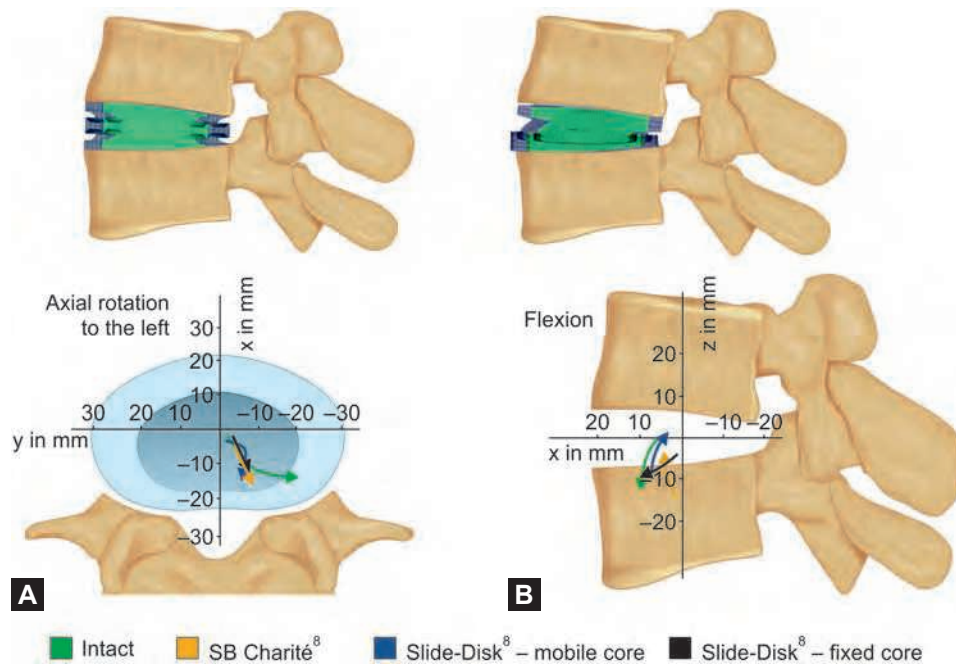
It can be speculated that the center of rotation seems to be of special interest. The principles can be investigated best with well-validated or better calibrated finite

element models (Figs. 91.8A and B). Our own calculations with unconstrained disc prostheses and semiconstrained versions that allow translations of the core in lower end-plate of the implant in both the anteroposterior and the laterolateral direction or a fixed core showed that all implant designs demonstrated a moving center of rotation.³⁹ Except for axial rotation, the unconstrained and constrained configurations mimicked the intact situation. In axial rotation, only the semiconstrained implant that allowed translation of the core reproduced the intact behavior. Results partially support our hypothesis and imply that different implant designs do not lead to strong differences in the range of motion and the location of the center of rotation. In contrast, facet forces appeared to be strongly dependent on the implant design.³⁹ However, due to the great variability of facet forces reported in the literature, together with our results, it could be speculated that these forces may be more dependent on the spines geometry rather than a specific implant design.

The greater the number of artificial disks that are implanted in one patient, the greater the correlation of flexion and extension motion is to the intact condition.⁴⁰ Deviations from optimal implant position lead to unfavorable kinematics, high facet joint forces, and even to lift-off phenomena. Therefore, multilevel TDA should, if at all, only be performed in appropriate patients with good muscular conditions and by surgeons who can ensure optimal implant positioning.

Nucleus Replacement Implants

If the disc is not strongly degenerated, i.e. the annulus is still more or less intact, then nucleus implants may be used as an alternative to a total disc prostheses.⁴¹ This concept has the advantage that existing anatomical structures can be preserved, e.g. the annulus, the end-plates of the vertebral bodies and the ligaments. Besides maintaining mobility, a nucleus replacement has the potential to restore disc height and thereby the nominal stresses and strains of the collagen fibers in the annulus. From a historical perspective, in the 1950s and early 1960s the nucleotomized cavity was refilled with polymethylmethacrylate (PMMA), silicone or stainless steel balls if a nucleus implant was desired.⁴²⁻⁴⁴ The intention of nucleus replacement is to restore the disks biomechanical function, prevent pain and further disc degeneration. The implants also should be biocompatible and nontoxic. Because of the different materials that are used today, it is possible to divide nuclear implants into mechanical, polymer and tissue engineered implants (Fig. 91.9).⁴⁵



Figs. 91.8A and B: (A) SB Charité III disk—representing an unconstrained design. (B) Slide disk—also representing an unconstrained design, but additionally the core can move almost freely within the transversal plane.

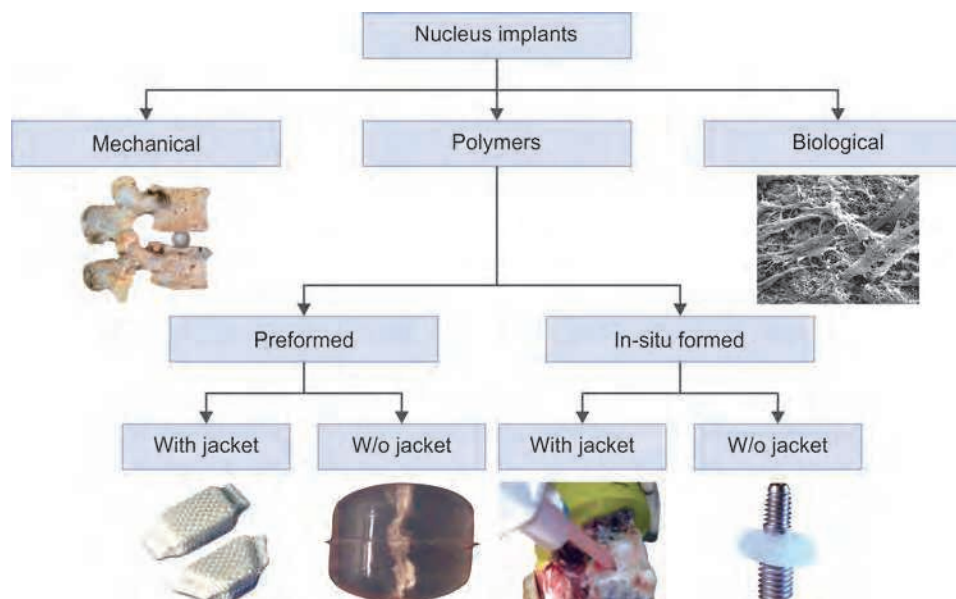
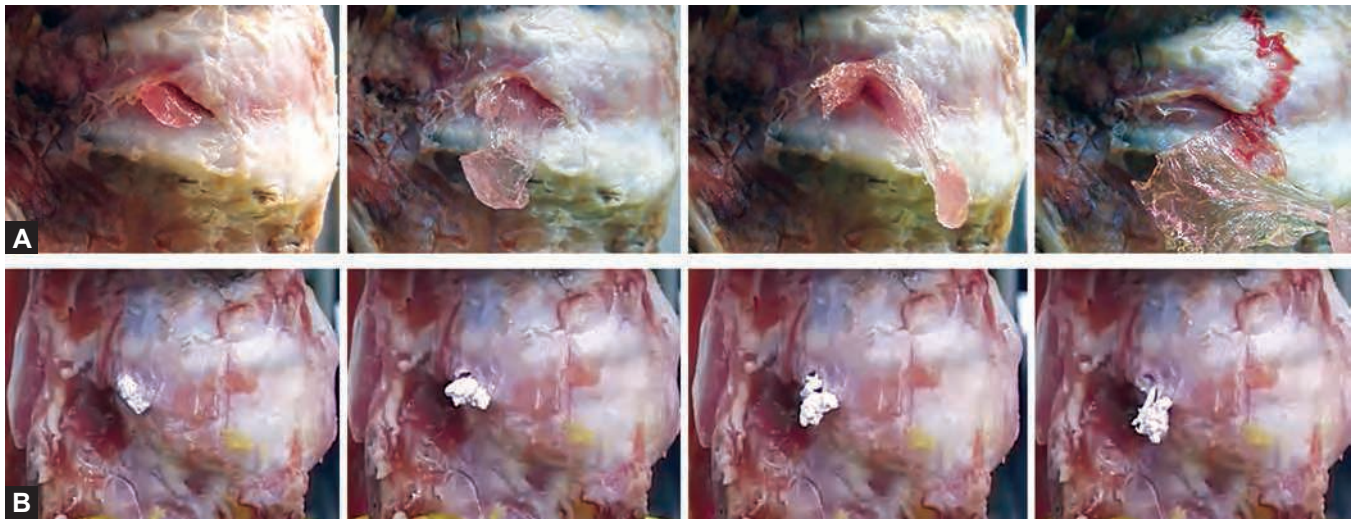


Fig. 91.9: Classification scheme for different nucleus implants concepts.⁴⁸

In our own studies, we were able to show that the original flexibility and disc height of a denucleated L4-L5 motion segment can be restored with the implantation of a nucleus implant.⁴⁶ However, the kinematics, i.e. the quality of the motion, can hardly be predicted. It has been

shown that an implant may restore ideal coupled motion patterns, or reproduce a hinge joint motion with negative effects on facet joint motion.⁴⁷

Definitively the biggest problem with nucleus arthroplasty is the risk of extrusion (Figs. 91.10A and B).⁴⁸



Figs. 91.10A and B: Two video sequences of nucleus implant extrusion. (A) A nucleus replacement implant based on a two-component silicone gel during a cyclic loading test. After 20,000 load cycles, the implant was completely extruded; (B) A tissue-engineered nucleus replacement implant, which basically consists of condensed collagen type-I matrix, extruded already during a flexibility test (lateral bending) in a spine tester.

Almost all nucleus devices, which were tested *in vitro* in our laboratory, could be extruded in our cyclic loading setup. The tissue engineered implants made of collagen matrix were squeezed out after only a few loading cycles if the hole produced by the nucleotomy was in the range of 6–7 mm.⁴⁸ Textile implants proved to maintain their stability longer, but still were extruded with a low number of load cycles. A similar finding was found with *in situ* formed implants. Some of them could be provoked to extrude, while some maintained their position up to 100,000 load cycles. Unfortunately, it could not be clarified whether this problem could be explained by the shape or the size of the implant or the size of the nucleotomy. Only the knitted prosthesis demonstrated reasonable stable fixation, because the filaments of the implant subsided and thus attached mechanically into the cartilaginous part of the endplate.⁴⁹

Methods of Annulus Sealing

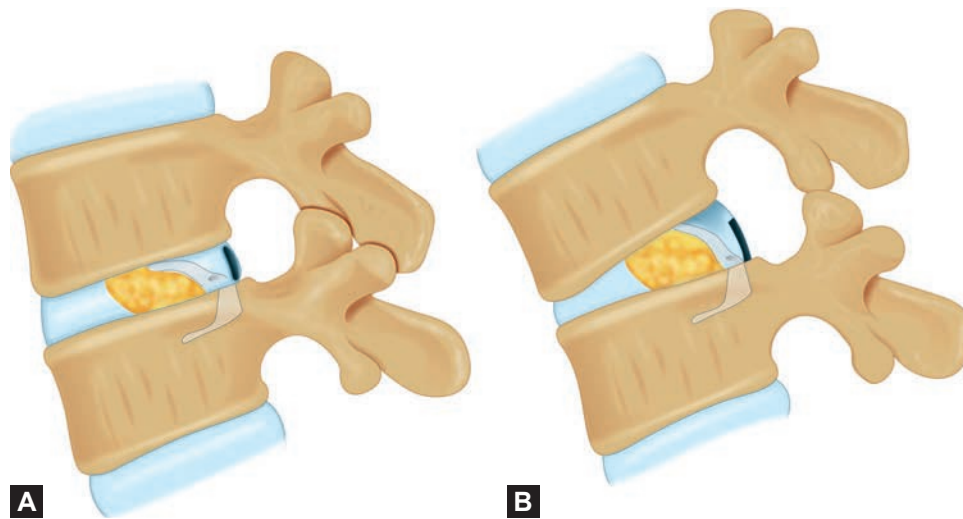
If nucleus implants are to remain stable within the disc or if a recurrent disc herniation is to be prevented, reliable sealing techniques are required that can withstand extremely high pressures of at least 2.3 MPa (333 PSI) of hydrostatic pressure.⁵⁰ Considering how difficult it is to close a hole in a car tire where a pressure of 0.23 MPa (33 PSI) is present, it is challenging to overcome pressures that are 10 times greater than that in the human disk.

Suturing and gluing the annulus defect increase the number of load cycles until an implant is extruded.⁵¹

If gluing and suturing are combined, it appeared to allow up to 40,000 load cycles before an extrusion occurred; however, a sufficient sealing could not be guaranteed. Until now, most nuclear replacement implants have not proven to be reliable and have been taken off the market. Therefore, it is extremely important to test these implants with an adequate testing model. We established a human herniation model that reliably produced and generated a nucleus implant extrusion during cyclic loading, which could only be guaranteed in specimens with minimal disc degeneration.⁵² The only sealing device that has shown to work adequately is the Barricaid implant (Intrinsic Therapeutics), which appears to prevent the nucleus from reherniating under our testing conditions (Figs. 91.11A and B). These findings reaffirm the importance of critically investigating new annulus closure devices and nucleus replacement techniques before they can be used clinically in a patient.

CONCLUSION

Each technology designed to preserve spinal motion behaves in its own unique way biomechanically. In order to prove the potential advantages of an implant, it should be tested in *in vitro* experiments before it is applied clinically in a patient. Unfortunately, only few prospective and controlled clinical trials (class I or II evidence) are available on these devices, or the follow-up time clinically is too short for a definitive understanding of the devices performance and durability.



Figs. 91.11A and B: Annulus sealing with the Barricaid implant.

Despite the limitations of biomechanical in vitro testing and complementary finite-element-calculations, such investigations may provide interesting results that can stimulate academic discussion. Sometimes these tests demonstrate that the implants behave as suggested. Sometimes the results help to optimize the technology. Sometimes it can be shown that specific features do not lead to significant differences in performance, and sometimes the results do not support the promised behavior of an implant design. Therefore, preclinical tests should always be performed using appropriate methodology to truly understand the limitations of a spinal implant.

ACKNOWLEDGMENTS

This chapter cites a series of different experimental studies that were carried out by different teams. Therefore, I would like to acknowledge all coworkers who actually did the work in these studies: Werner Schmölz, Jörg Huber, Thomas Nydegger, in the DYNESYS study; Jörg Drumm, Kim Häussler, Annette Kettler, and Karin Werner in study about interspinous implants; Werner Schmölz, Hendrik Schmidt, Karin Werner, Michael Tauber, Lutz Claes in the TOPS study; Balkan Cakir, Werner Schmoelz, René Schmidt, Wolfhart Puhl, Marcus Richter investigated the total disc prosthesis; Annette Kettler, Marcus Mohr, Sinead Kavanagh, Allison Bain, Britt Norton evaluated the prosthetic disc nucleus; and Frank Heuer and Cornelia Neidlinger-Wilke supported the study with the tissue engineered nucleus. Anulus Sealing was studied with Frank Heuer and Lena Ressel.

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KEY POINTS

- Dynamic fixator
- Interspinous implant
- Total posterior arthroplasty
- Total disc arthroplasty
- Nucleus replacement
- Annulus sealing

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Posterior Pedicle-Based Dynamic Stabilization of the Lumbar Spine

Bernhard Jeanneret, Stefan Schaeren

Snapshot

- » History
- » Own Experience
- » Indication for Surgery
- » Surgical Technique
- » Summary of Our Results

DEFINITION

Posterior pedicle screw-based dynamic stabilization devices (PDS) are posterior, more or less flexible implants, which originally were intended to control motion and/or load bearing of the motion segment, in order to address instability and the resultant back pain.¹ However, back pain was never really well treated with such devices. Excellent results are obtained when a symptomatic spinal stenosis with degenerative spondylolisthesis is decompressed and stabilized with such a PDS.

HISTORY

Graf developed the first system in 1992 to stabilize and treat painful motion segments.² It used braided polyester cables looped around screws to provide stability while allowing some motion. Several reports have been published on the clinical results of this device: the outcomes have been inconsistent. Later on, Gilles Dubois developed the Dynesys system marketed by Zimmer.³ This system uses semirigid polyurethane spacers over a polyethylene cord put under tension and connected to pedicle screws. This system also was intended to treat low back pain. The clinical results, however, were mixed. Grob et al. published a retrospective study on 50 patients who were treated with the Dynesys system for symptomatic degenerative disc disease or stenosis with associated instability.⁴ Back and

leg pain improved in 67% of patients; however, functional capacity only improved in 40% of the patients with a high rate of reoperation (19%). Grob, therefore, stopped using these implants. In Switzerland, Dynesys was not only used for 1–2 levels, but some surgeons used it for stabilization of 4–5 levels, with sometimes deleterious results (unpublished data).

Today, a variety of semirigid pedicle-based implants have been introduced, including AccuFlex (Globus Medical, Inc.), CD-Horizon Legacy PEEK rods (Medtronic), ExpEDIUM PEEK rod (DePuy Synthes), Scient'X's Isobar, Stabilimax NZ device (Applied Spine Technologies, Inc.), and the Cosmic posterior dynamic system (Ulrich GmbH & Co. KG) to name a sampling. The most extensively investigated device, however, is the Dynesys system.

OWN EXPERIENCE

Our experience was similar to the one of Grob et al.⁴ We never implanted Dynesys to treat low back pain, but had to remove Dynesys implanted by others because of persistent pain after stabilization with this system. During removal of such implants, we discovered that some motion segments bridged by the so-called dynamic system were spontaneously fused. We, therefore, thought that these implants could be used for stabilization of degenerative spondylolisthesis in addition to decompression of a spinal stenosis, making bone grafting unnecessary. In 2000, we

evaluated our first series of patients, which we published in 2006 with a minimum follow-up period of 2 years.⁵ The same group of patients were followed up at 4 years.⁶ Currently, we are reviewing our patients at 10-year follow-up. Our results have been satisfactory and therefore we apply pedicle-based dynamic stabilization in addition to decompression as our standard stabilization technique for degenerative spondylolisthesis, when decompression has to be performed because of symptomatic spinal stenosis.

Meanwhile, several other publications have shown that pedicle-based dynamic systems may be used with excellent results for the stabilization of degenerative spondylolisthesis, without any bone supplementation, making surgery easier for the patients and for the surgeon.⁷⁻⁹

INDICATION FOR SURGERY

We use the dynamic pedicle stabilization technique exclusively for the stabilization of degenerative spondylolisthesis with symptomatic spinal stenosis undergoing surgical decompression. All our patients have spinal claudication unresponsive to nonsurgical treatment (nonsteroidal inflammatory drugs, epidural steroid injections, physiotherapy, etc.).

SURGICAL TECHNIQUE

Decompression

The most important part of our surgical treatment is the proper decompression of the spinal canal. All stenotic levels are decompressed. We use the classical midline approach. The laminae and articular masses are exposed on both sides. The interspinous ligament and the *ligamentum flavum* of the segments to be decompressed are removed. Usually, a few millimeters of the cranial part of the caudal lamina as well as inferior parts of the cranial lamina are removed. We use an interspinous spreader to widen the interspinous space and allow easier decompression. The dura and the exiting nerve roots are fully decompressed, the roof of the lateral recess is removed to the medial pedicle border, and the caudal foramen is enlarged if necessary. The cranial foramen is decompressed as well if necessary.

Stabilization

After thorough decompression of all stenotic segments, stabilization is performed only at the level of the degenerative spondylolisthesis (Figs. 92.1 and 92.2). We use the dynamic system exclusively for the stabilization of

degenerative spondylolisthesis at one and at maximum two levels. The pedicle screws are inserted under fluoroscopy and the dynamic connectors (polyurethane sleeves for the Dynesys system, PEEK rods for the ExpEDIUM system) are mounted. To allow proper insertion of the Dynesys sleeves or PEEK rods, the degenerated and hypertrophic joints of the spondylolisthetic segment must usually be trimmed somewhat. No distraction or compression is needed, and most importantly no attempt to reduce the degenerative spondylolisthesis is performed. This would destabilize the motion segment and screw pull-out could be the result. No bone grafting is performed. The wound is closed in layers over three drains—two subfacial and one subcutaneous.

Postoperative Management

The patient is mobilized the first day after surgery with a soft lumbar orthosis for 3 months to allow healing of the soft tissues and bony incorporation of the screws. An X-ray is performed at 3 months. At this stage, the patient is allowed to start with his normal daily activities. Usually, no physiotherapy is needed.

SUMMARY OF OUR RESULTS

At 2 and 4 years, visual analogue score and walking distance improved significantly ($P < 0.001$). Radiographically, spondylolisthesis did not progress and the motion segments remained stable even in three patients who showed slight screw-loosening at 2- and 4-year follow-up. At 4-year follow-up, 47% of the patients showed some degeneration at adjacent levels. Overall, patient satisfaction was very high as 95% would opt again for the same treatment.

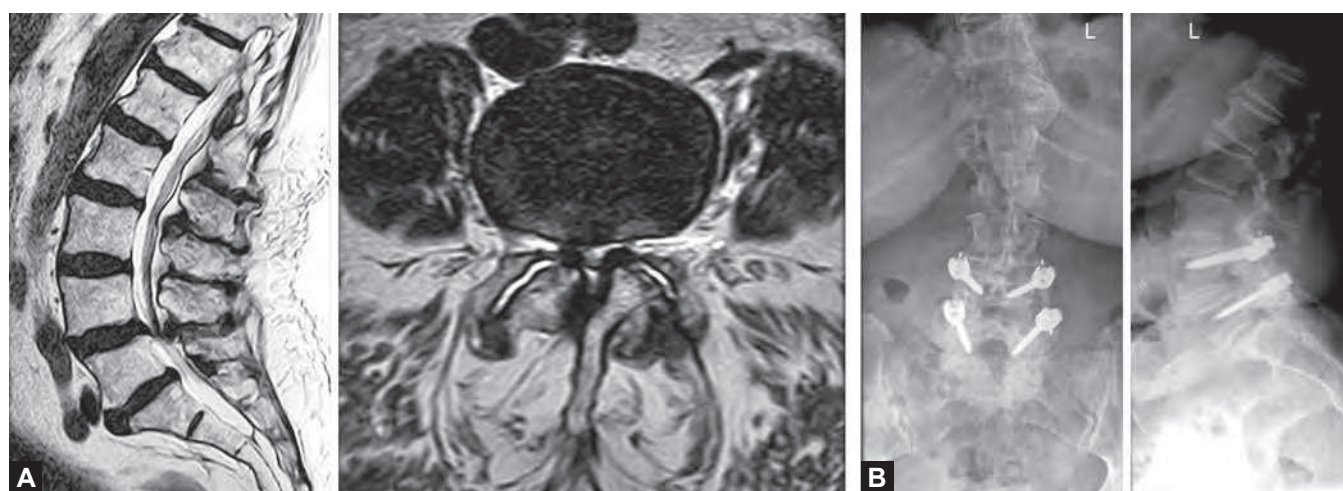
At 10-year follow-up (range 10–13 years), spondylolisthesis did not progress and the motion segments remained stable. Nearly two-thirds of the patients, however, now showed a slight to moderate increase in adjacent segment degeneration and 8% of the patient population had required further surgery because of symptomatic adjacent segment degeneration (Figs. 92.3A and B). However, 90% of patients still would undergo the surgery again.

DISCUSSION

In our experience and based on the literature, dynamic pedicle-based stabilization of lumbar spinal segments is not successful in the treatment of low back pain. However, it can be successfully used for the stabilization of degenerative spondylolisthesis when spinal stenosis has to be



Figs. 92.1A to C: An 80-year-old woman with typical spinal claudication. She can only walk about 50 m. After this distance, the pain in the leg is so intense that she has to sit down. Also, her legs become very weak during walking. The myelogram (A) shows spinal stenosis L2/3 and stenosis at the level of the degenerative spondylolisthesis L3/4. A decompression L2/5 was performed and the degenerative spondylolisthesis L3/4 was stabilized with Dynesys (B). Two years after surgery, the patient is pain free and the implants are stable (C).



Figs. 92.2A and B: A 79-year-old woman with spinal claudication with leg pain L5 on both sides for 2 years while walking. Walking without help is only possible indoors; outdoors she can walk slowly for 500 m with a wheeled walker. The magnetic resonance imaging (A) shows a marked spinal stenosis at the level of the degenerative spondylolisthesis L4/5. The stenosis L4/5 was decompressed and the degenerative spondylolisthesis L4/5 stabilized with Expedium Peek rods. The 2-year follow-up (B) shows stable implants.



Figs. 92.3A and B: A 69-year-old man, 10 years after decompression of a spinal stenosis L4/5 and stabilization with Dynesys because of the degenerative spondylolisthesis. The patient was pain free during 9 years after surgery and presented to the 10-year follow-up with some leg pain and leg weakness while walking for the last 2 months. The X-rays (A) show stable implants and a spontaneous posterolateral fusion L4/5 (no bone grafting had been performed at index surgery). The myelo-CT (B) shows a spinal stenosis L3/4, the level above the stabilized segment.

treated surgically. Compared to posterior fusion techniques using rigid implants, PDS does not need bone grafting; therefore, PDS is quicker and less invasive since there is no donor site morbidity.

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Total Facet Replacement

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Snapshot

» Total Facet Replacement Devices

INTRODUCTION

The functional spinal unit (FSU) consists of the intervertebral disc, the cranial and caudal vertebrae, the interconnecting ligaments, and two facet joints. While the motion-preserving concept and clinical experience with lumbar total disc replacement (TDR) have evolved over the past several decades, total facet replacement (TFR) is relatively new in the field of spinal surgery. A TFR implantation involves the complete removal of bilateral facet joints (facetectomy) and prosthetic replacement, to be distinguished from lumbar posterior dynamic stabilization devices (to be discussed in a separate chapter) that preserve the in situ facet joints and augment the motion of the FSU through a flexible motion-preserving design.

The TFR procedure is proposed as an alternative to posterior spinal fusion in patients with degenerative spinal conditions. As an emerging technology, the indications and available devices are evolving at present. Potential future applications of a TFR system may include (1) complete 360° arthroplasty of the motion segment (concomitant TDR and TFR) that will entail complex biomechanical and wear related considerations and (2) TFR systems for patients in which facet joint arthropathy (Fig. 93.1) requires a wide decompression (facetectomy) for adequate decompression of the neural elements. The current generation of TFR devices and clinical trials has been designed for the latter indication.

The facet joints bear approximately 15% of the physiologic axial load of the spine in the standing position with

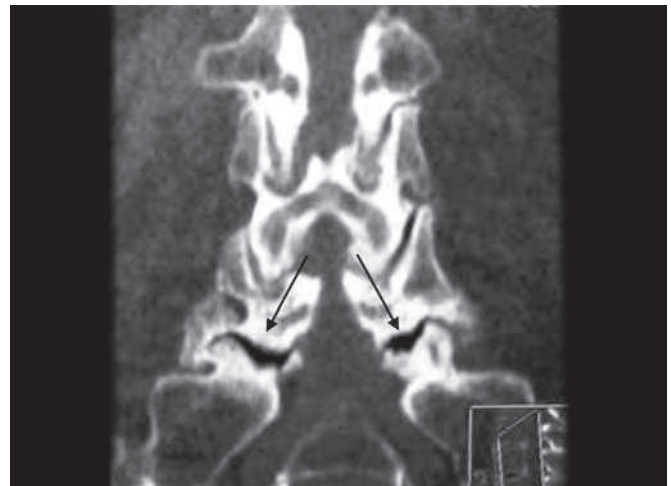


Fig. 93.1: Computed tomography images of facet joint arthropathy on coronal view. Arrows point to facet joint arthritis.

the remainder transmitted through the anterior column and the intervertebral disk. The proportion of load transmitted through the facet joint increases in extension and as the degeneration of the motion segment progresses.^{1,2} Isolation of the “pain generator” in degenerative conditions causing low back pain remains challenging, as does the diagnosis of patients with “facetogenic” pain. Computed tomography assessment is better suited to diagnose facet arthropathy;³ however, radiographic facet degeneration may be seen in more than half of asymptomatic patients,⁴ which highlights the diagnostic conundrum. Not surprisingly, despite encouraging cadaveric biomechanical



Fig. 93.2: Drawing of posterolateral view of the ACADIA facet replacement system device.



Fig. 93.3: Lateral plain radiographic view of the ACADIA facet replacement system device.

data and theoretical underpinnings, the clinical results of facet arthroplasty have been mixed. As such, the current generation of TFR implants with its varied material composition and design strategy will likely undergo multiple iterations of modifications as a broader clinical experience accumulates. The following discussion will focus on the design features and current clinical data on TFR devices.

TOTAL FACET REPLACEMENT DEVICES

ACADIA Facet Replacement System

The acadia/anatomic facet replacement system (AFRS) implant (Facet Solutions, Inc., Hopkinton, MA, acquired by Globus Medical, Audubon, PA, in January 2011) is a pedicle screw-based design that is composed of superior and inferior facet implants (Fig. 93.2). The cobalt-chromium-molybdenum articulating facet surfaces are linked by a crossbar that spans the inferior facet implants from left to right.

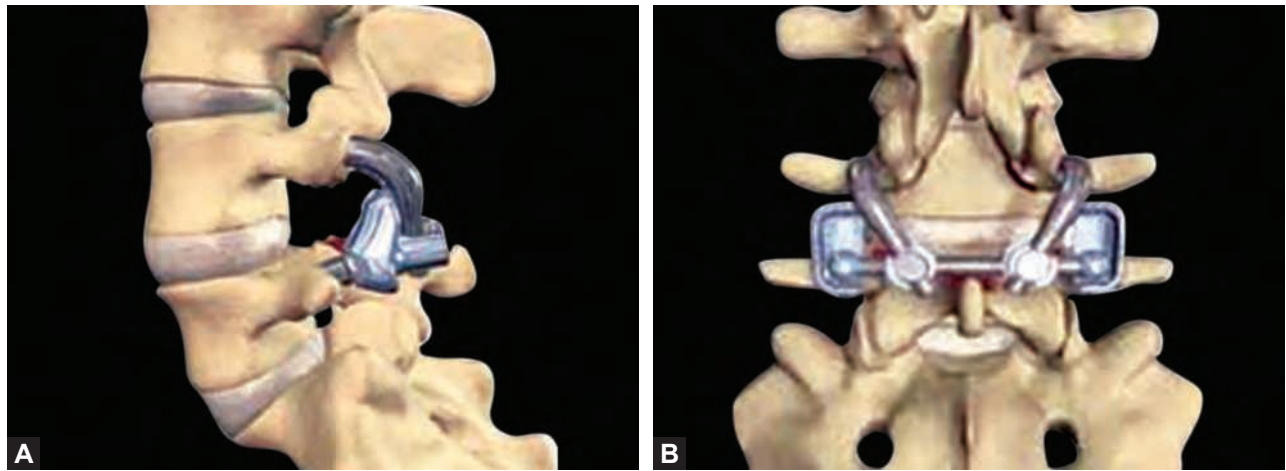
The AFRS is being evaluated as part of a phase III Food and Drug Administration (FDA) investigational device exemption (IDE) clinical trial that is currently recruiting with an estimated enrollment of 300 patients. Patients were randomized 2:1 either to the investigational ACADIA device (Fig. 93.3) or to instrumented posterolateral fusion (PLF). Several of the inclusion criteria are patients with lateral, lateral recess and/or central stenosis, who failed >6 months of nonoperative management, and who are the candidates for a full facetectomy for decompression with preservation of disc height (measuring ≥ 4 mm). Patients with prior lumbar spinal surgery, spondylolisthesis >grade I,

and retrolisthesis were excluded. Primary outcome measures are improvement in Zurich Claudication Questionnaire Physical Function, and Symptom Severity scores, lack of device-related serious events, maintenance or improvement of neurological status, and no device failures requiring revision, removal, reoperation, or supplemental fixation.⁵ Final data collection was scheduled for October 2013.

In 2012 early results of the ACADIA IDE study were reported. These preliminary data indicated that improvements were seen in all function and pain outcome measures at 12 months postoperatively and high levels of patient satisfaction for both the study group and the PLF control group.⁶ The 100th patient in the IDE study was enrolled in 2012 and peer-reviewed publication and longer follow-up of these cohorts are pending at the time of writing of this chapter.

Total Facet Arthroplasty System

The total facet arthroplasty system (TFAS) implant (Archus Orthopedics, Inc., Redmond, WA, acquired by Facet Solutions, Inc., Hopkinton, MA, in 2009, acquired by Globus Medical, Audubon, PA, in 2011) is a nonfusion spinal implant composed of a metal-on-metal articulation with two cephalad bearings that articulate with two caudal housings (Figs. 93.4A and B). The caudal housings are linked by a cross-arm assembly that is anchored to the cephalad components by a medial locking mechanism. The caudal housings permit flexion and extension as the spherical components translate throughout the base of the housing in the metal-on-metal articulation.



Figs. 93.4A and B: Drawing of lateral view (A) and posterior view (B) of the total facet arthroplasty system device.



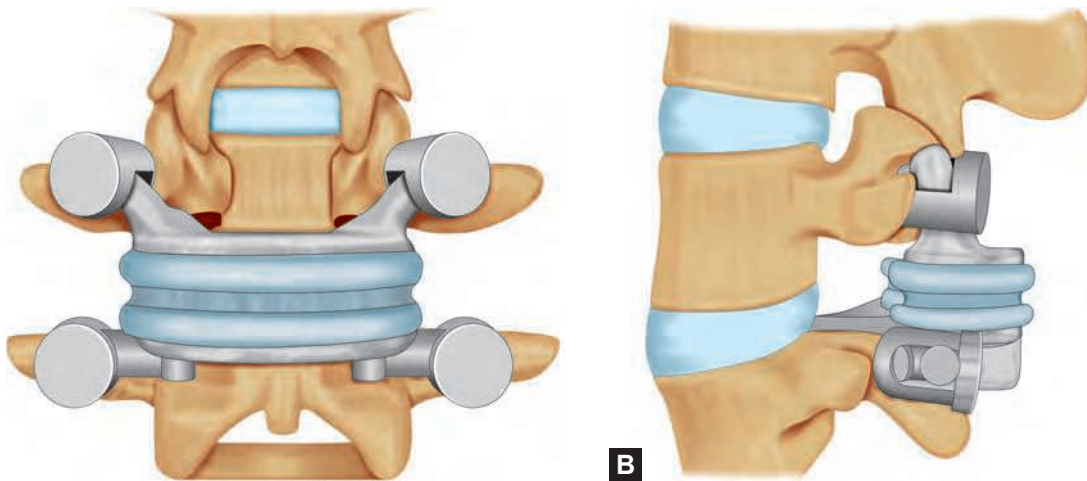
Fig. 93.5: Anterior-posterior (left) and lateral (right) plain radiographs of the total facet arthroplasty system device in vivo.

The implant was designed to replace the diseased facets in patients with severe spinal stenosis that would require a wide decompression involving complete removal of the facet joints (Fig. 93.5). Purported advantages were a more normal physiologic motion profile at the operative and adjacent segment and the avoidance of donor-site iliac crest autograft morbidity that may be required for posterolateral fusion.

The TFAS device to date is the most studied TFR implant in the peer-reviewed literature in preclinical biomechanical studies. Cadaveric flexibility tests were reported on an intact and an injury model after stabilization with the TFAS and posterior pedicle screw systems at L4–L5 in 2007. Range of motion (ROM) with the TFAS was less than the intact specimen in all planes of motion (81% in flexion,

68% in extension, and 88% in lateral bending) except for an increase ROM in rotation (128% axial rotation).⁷ Following complete decompression (laminectomy and facetectomy) at L3–L4, TFAS was reported to restore near-normal motion at the adjacent motion segments.⁸ Reproduction of intact-like anterior column load-sharing as measured by disc pressure was reported in a cadaveric model; however, there were differences in implant moments between TFAS and a standard pedicle screw implant system.⁹

The phase III FDA IDE study of the TFAS device started in 2005 with an estimated enrollment of 450 patients with persistent leg symptoms, including pain, numbness, burning, or tingling for a minimum of 6 months with no more than three levels of degenerative lumbar stenosis requiring decompression. The study was later discontinued for reported financial reasons in 2011.^{10,11} Preliminary data from the TFAS IDE study in 2012 reported on 59 patients who underwent TFAS procedure and were instrumented at either L3–L4 or L4–L5. A statistically significant decrease in flexion-extension motion that was observed at the operative level between preoperative and postoperative radiographs at 12 months, however, was restored to near-normal ROM at the 24-month time point. Both the cranial and caudal adjacent levels demonstrated similar motion to preoperative at both the 12- and 24-month time points.¹² A report emerged of two patients from the IDE study with stem fracture of the TFAS implant at 9 months and 27 months postoperatively. Both patients were implanted with TFAS at the index surgery for an indication of L4–L5 spondylolisthesis with stenosis. The authors suggested that the biomechanical mechanism of TFAS breakage might be similar to pedicle screw breakage in the setting of



Figs. 93.6A and B: The total posterior facet replacement system is designed with two titanium plates and an outer polycarbonate urethane capsule. The capsule contains an articulating PcU component that is intended to duplicate the function of the facet joints. *Source:* Reproduced with permission, Elsevier Ltd, Oxford, UK.

pseudarthrosis indicating fatigue failure and three-point bending stresses. Both patients were revised with transposas lateral lumbar interbody fusion uneventfully.

Total Posterior Facet Replacement

The total posterior facet replacement (TOPS) implant (Impliant Ltd., Ramat Poleg, Israel, acquired by Premia Spine, Ltd, Herzela, Israel) is a pedicle screw-based facet arthroplasty system consisting of metal and plastic components. A polyurethane articulating construct allows motion between two titanium plates that are secured to the motion segment by four hydroxyapatite-coated polyaxial pedicle screws. The crossbars are joined together by an elastic component that is designed to transmit loads between the components (Figs. 93.6A and B).

Biomechanical studies of the TOPS device in human cadaveric specimens at L4–L5 demonstrated 85% of the intact specimen ROM was restored in the sagittal plane and near-complete restoration of motion in lateral bending and axial rotation.¹³ A subsequent report described ROM values with the TOPS System that were not significantly different from the intact values.¹⁴ Cadaveric evaluation of intervertebral disc bulging and anular fiber strains with the TOPS device was associated with a slight decrease in fiber strain (5%) compared to intact specimens in flexion, but maximum fiber strains doubled from intact (6.5–13.8%) in lateral bending.¹⁵ Both were considered to be within the physiologic range by the authors.

Preliminary clinical data of 29 patients undergoing tops from the nonrandomized multicenter (uncontrolled) pilot

study was reported with mean surgical time of 3.1 hours for a single-level procedure (L3–L4 or L4–L5 TOPS implant following complete bilateral total facetectomy and laminectomy).¹⁶ Oswestry Disability Index decreased compared to baseline by 41% at 1 year and the VAS score declined 76 mm with reported radiographic analysis that showed restoration of lumbar motion, preservation of disc height, and no evidence of implant loosening. Longer outcomes have not been reported to date.

The FDA prospective randomized controlled IDE study started in May 2008 and was designed to enroll an estimated 450 patients aged 40–75 years with VAS leg pain of at least 40/100 at baseline and Oswestry Questionnaire score of at least 40/100 at baseline.¹⁷ The study was temporarily suspended in 2008 voluntarily by the manufacturer after a report of a device-related failure due to the inability of the components to sustain the in vivo shear loads.¹⁸ Reportedly a design modification was made at that time to better withstand these loads. Peer-reviewed publication of the TOPS IDE trial has not been reported to date and the device is not currently commercially available in the United States.

CONCLUSION

The physiologic demands on a facet arthroplasty device far exceed those of a rigid fixation fusion construct. While pedicle screw instrumentation of a motion segment is required to withstand implant moments and loading conditions until fusion has occurred, a TFR implant must withstand these forces indefinitely. Some authors have suggested that indications for this technology in a “stand-alone” fashion

may be limited given that the intervertebral disc is left in situ and represents a potential nociceptive source. Preservation of motion with an instrumented pedicle screw-based system holds theoretical concern for three-point bending stresses on the “stem” of the implant and subsequent fatigue failure over the hundreds of thousands of in vivo motion cycles that the implant must tolerate. Indeed, fatigue failure of the implant resulting in stem fracture was reported with the TFAS implant. Little is known at present about the in vivo wear patterns of the current TFR implant designs and the associated long-term clinical sequelae. To date, there is no facet arthroplasty device that has been approved by the FDA, yet intrigue for the potential to completely replace the facet joints alone, or in combination with the entire three-joint complex of the FSU, remains high.

KEY POINTS

- Total facet replacement is considered investigational at the present time. There are currently no FDA-approved TFR devices.
- Biomechanical in vitro data suggest near-normal duplication of the operative and adjacent motion segments with TFR devices is feasible.
- Implant failure remains a theoretical concern for pedicle-based facet arthroplasty systems. Case reports have emerged of stem fracture of TFR designs.
- The ideal TFR device will re-create normal physiologic range of motion at the operative and adjacent motion segments with minimal wear and will be able to withstand the bending moments and loading conditions of the spinal motion cycle without undergoing fatigue failure.
- Future applications of TFR may include 360° replacement of the spinal motion segment—simultaneous TDR and TFR.

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Lumbar Disc Replacement

Michael F Duffy, Jack E Zigler

Snapshot

- » Biomechanical Considerations
- » Clinical Presentation and Diagnostic Evaluation
- » Surgical Technique
- » Complications
- » Postoperative Care
- » Discussion

INTRODUCTION

The modern era of lumbar arthroplasty began in East Berlin in the early 1980s, with the development of the SB Charité disc (later manufactured by LINK; Hamburg, Germany) by Karin Büttner-Janz and Kurt Schellnack.^{1,2} Through several iterations, it was first implanted in patients in Europe in the mid-1980s with mixed results. Patient selection and technical issues with access and implantation (mobilization and placement) led to some poor clinical results. The intrinsic unconstrained design of the Charité implant was philosophically appealing, but the dramatic in vitro demonstrations of its ability to move the center of rotation did not translate into favorable in vivo results when it was implanted into a surgically destabilized segment.

Despite the negative 1990s response to lumbar arthroplasty outside the United States, a Food and Drug Administration (FDA) investigational device exemption (IDE) trial of Charité controlled by comparison to anterior lumbar interbody fusion (ALIF) with stand-alone paired BAK cages (Zimmer Spine, Austin, TX) started in 2000.³ This was the first premarket approval (PMA) arthroplasty study in the United States. The Charité study was initiated by Link and the arthroplasty technology was ultimately acquired by DePuy-Johnson & Johnson.

Also in the late 1980s and early 1990s, Thierry Marnay, a French orthopedic surgeon, was working on the

development of the ProDisc implant. Based in southern France and on the western side of the Iron Curtain, he was only marginally aware of the work at the Charité Hospital in East Germany. Marnay's design was a keeled, semiconstrained implant, and he and a colleague implanted 93 devices in 64 patients between 1990 and 1993. They then had the academic restraint to stop implanting and to clinically follow those patients. In the late 1990s, a US company (Spine Solutions, Inc., New York) independently reviewed radiographs, interviewed Marnay's patients, and used that data to convince the FDA to allow them to start a multicenter trial in the United States comparing ProDisc to a 360° (combined anterior and posterior) spinal fusion. Both one- and two-level study arms were initiated. The first surgery of the single-level arm occurred in October 2001, and the first two-level surgery in the United States was performed in January 2002, both at the Texas Back Institute.

Other lumbar devices have subsequently pursued the PMA track with prospective randomized multicenter trials, including the Maverick (Medtronic, Memphis, TN) not commercially available in the United States, the Flexicore (IDE withdrawn by Stryker Spine, Allendale, NJ), the Kineflex-L (SpinalMotion, Mountain View, CA), the Active-L (Aesculap, Center Valley, PA), and the Freedom (Axiomed, Garfield Heights, OH) devices, all in FDA queue in final data collection. The Kineflex study was the first to randomize to another total disc replacement (TDR) (Charité).

Active-L randomized to either Charité or ProDisc, and Freedom randomized to ProDisc. As of this date, only Charité and single-level ProDisc-L have achieved FDA approval in the United States. With the worldwide withdrawal of Charité in 2011, only ProDisc-L is currently commercially available for implantation in the United States. The Charité withdrawal from the market was primarily due to a business decision occurring around the time Depuy acquired the ProDisc through its merger with Synthes.

Two-year multicenter IDE data has been published for Charité, ProDisc, and Maverick.³⁻⁵ Five-year multicenter outcomes data has been published for Charité and ProDisc-L.⁶⁻⁸ In a prospective, randomized fashion, arthroplasty patients demonstrated improved outcomes using standard measurement instruments such as the Oswestry Disability Index (ODI) and visual analog scale (VAS) assessing pain compared to the fusion cohorts at 2 years for all three devices.³⁻⁵ At 5 years, both the Charité and ProDisc clinical results were maintained at similar levels to the 24 month data.^{6,8} Reoperation rates at both index and adjacent levels were lower in the arthroplasty patients as well.

Most recently, Zigler et al.⁹ have shown that radiographic degeneration at the adjacent level is statistically significantly reduced at 5 years when comparing patients randomized to ProDisc-L versus 360° fusion. The multiparameter adjacent level changes, graded by independent radiologists, were three times greater in the fusion group.

Despite very strong clinical and radiographic data showing benefits with arthroplasty, adoption of this technology has been slow. A significant impediment has been reluctance on the part of major insurance carriers to authorize payment for this technology, continuing to consider it “investigational and experimental” despite FDA approval in 2004 and 2006 for Charité and ProDisc, respectively. Another impediment to adoption is the need for an access surgeon to provide safe and consistent anterior exposure of the lower lumbar spine, since few spine surgeons choose to do their own approaches. A final challenge to more widespread adoption has been the relatively poor reimbursement for lumbar arthroplasty, even by those companies that have approval for its use. Reimbursement to the surgeon is approximately half that for a segmental fusion.

Several economic studies have shown that both direct and indirect costs are reduced with arthroplasty.¹⁰⁻¹³ Return to work, return to recreational activity, and post-operative pain medication use are all more favorable in the arthroplasty patient cohorts.

The scientific evidence in the published literature regarding the benefits of both arthroplasty and fusion is

very strong, thanks to these multicenter IDE studies. We now know more about the advantages of both lumbar fusion surgery and disc arthroplasty over nonoperative care for the treatment of functionally disabling degenerative disc disease of the lumbar spine. Historians will likely look upon the slow adoption of this technology with bewilderment, as the databases grow more robust with age, and the results are so strongly maintained in the literature.

BIOMECHANICAL CONSIDERATIONS

The spine has both a functional and protective role. First and foremost, the osseous anatomy of the spine functions to protect the thecal sac and neural structures. Simultaneously, the spine allows for coordinated motion in space. The forces acting on the spine (compressive, shear, tensile and torsional) are, under normal physiologic conditions, absorbed by anatomic restraints. White and Panjabi¹⁴ first described the functional spinal unit (FSU) or the spinal motion segment, which includes the adjacent vertebral bodies, the intervertebral disc and the two facet joints. The FSU also includes stabilizing ligaments but does not include muscles. The FSUs have been used extensively to study biomechanical properties of the spine. Load-displacement of the FSU is nonlinear, with two distinct regions—neutral zone and the elastic zone. These two zones exhibit differing biomechanical properties (Fig. 94.1). The neutral zone shows minimal internal

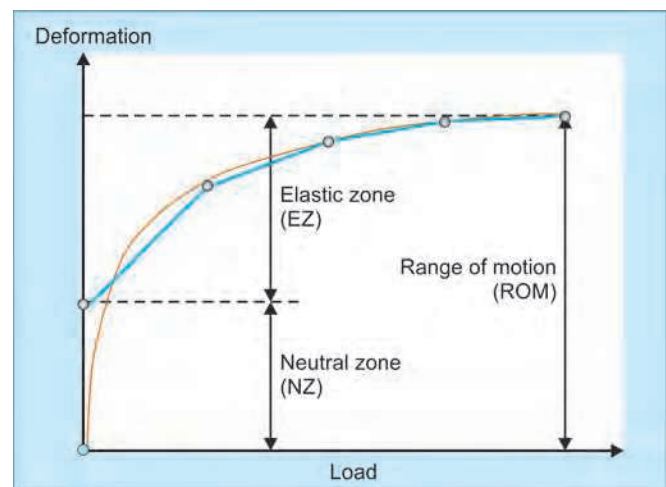
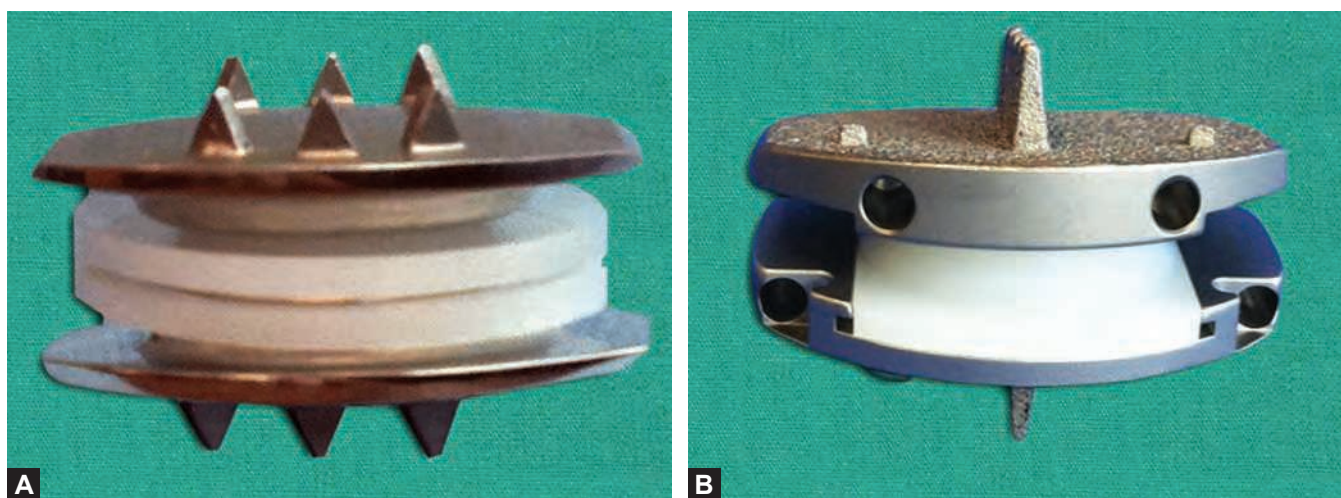


Fig. 94.1: A spinal segment is very flexible at low loads associated with the neutral zone and stiffens with greater load noted in the elastic zone. The load deformation relationship is a sharp curve, rather than linear.

Source: Adapted from Panjabi MM. The stabilizing system of the spine. Part II. Neutral zone and instability hypothesis. *J Spinal Disord.* 1992;5:390-97.



Figs. 94.2A and B: Images of an unconstrained lumbar arthroplasty device (A—Charité) and a semiconstrained device (B—ProDisc-L).

resistance during passive motion, where a small load produces a large displacement in space. From the end of the neutral zone to maximum resistance (the extent of motion allowed by the stabilizing structures) represents the elastic zone.^{15,16} The goal of the “perfect” TDR device is to reassimilate, as best possible, the normal segment motion and forces after removal of the anterior longitudinal ligament and the diseased intervertebral disc.

One of the most debated design fundamentals for artificial disc replacement is the concept of constraint. With the ProDisc-L, motion of the operative segment is limited by a ball-and-socket articulation design (semiconstrained device), whereas the mobile core design of the Charité disc (unconstrained device) imparts less restriction on motion (Figs. 94.2A and B). The mobile core translates freely within the device, thereby having motion that closely assimilates that of the normal spine. It was postulated that this design reduces stress imparted to the polyethylene core. The constrained device has 5 degrees of freedom (DOFs), whereas the semiconstrained device has 3 DOFs. These parameters potentially can have a profound effect on transmission of forces to the facet joints, vertebral endplates and possibly the adjacent intervertebral disc as well. Most lumbar TDR devices currently in FDA IDE trials employ some type of constraint.

Unfortunately, the biomechanical literature is confusing and often contradictory, making it difficult to draw steadfast conclusions about constraint. In theory, unconstrained devices are thought to have less stress imparted to the facet joints because they allow for motion resembling more normal motion. Rousseau et al.¹⁷ showed in a cadaveric

model that the degree of constraint of the implant does in fact affect load transfers and kinematics of the arthroplasty device, with the Charité implant having significantly less variation in the position of the instant axes of rotation (IAR). But in contrast to the general theory, this study showed that the forces imparted to the facet joints after implantation of an unconstrained device were found to increase significantly in all motions, especially in lateral bending. The more “physiologic” mapping of segmental motion with the unconstrained device has also been shown in other cadaveric studies in which the IAR resides in the posterior one-third of the disc space, as is found with intact segments.¹⁸ With the ProDisc device, the facet joints were found to be unloaded throughout flexion and extension.¹⁷ Interestingly a study assessing the IAR of fixed center semiconstrained devices found this design to impart more stress to the vertebral endplate due to incongruent surfaces. Finite element models have also been used to show the unconstrained devices impart less stress to the vertebral body and endplate, as well as lessen facet contact forces.¹⁹ In direct opposition, other finite element models have predicted increased facet joint forces using the unconstrained versus the constrained implants.²⁰ More long-term in vitro and in vivo mechanical analyses will be needed to determine which (if either) design is superior.

In regard to transmission of forces to the adjacent disc, many cadaveric investigations have shown both constrained and unconstrained total disc designs maintain or reduce the adjacent level disc pressures compared to fusion.^{18,21-24} How this correlates clinically is yet to be fully determined. The only level 1 evidence currently available

from the ProDisc IDE study shows radiographically at 5 years there is statistically less adjacent level degeneration with arthroplasty as compared to fusion.⁹ Other factors may play a significant role in adjacent segment degeneration (ASD), including the age of the patient at the time of implantation and genetic predisposition of the patient to develop advanced degeneration changes throughout the spine.

CLINICAL PRESENTATION AND DIAGNOSTIC EVALUATION

The ideal patient for lumbar arthroplasty is likely to be their 40s or 50s and has functionally disabling single-level lumbar disc disease at L3-L4 through L5-S1. The patient has failed at least 6 months of nonoperative care, has a pain VAS of $>7/10$, and has a bone density with a T-score of > -1.0 . From the published clinical trials, TDR was associated with early and significant improvement in both ODI and pain VAS, which was maintained during the 5 years follow-up.^{3,4,6,8} The typical patient has predominant low back pain. Patients frequently have pseudo-radicular leg pain (radiating to the buttocks and hamstring, but not below the knee). Patients who have disc space collapse after previous herniated nucleus pulposus (HNP), with or without prior surgical treatment, may have concomitant true radicular pain from vertical collapse of the foramen; however, these patients can still be considered for arthroplasty. The subset of ProDisc IDE patients with post-HNP disc space collapse (approximately one-third of the IDE population) actually had better outcomes than average.⁴ Even very collapsed discs can be mobilized, although more technically demanding, even in experienced surgical hands, as long as the facets are not excessively arthritic. Functional outcomes were not found to be related to preoperative disc height.

The most typical symptoms in the ideal patient are transverse lumbosacral pain associated with prolonged sitting or standing. These patients will typically give a history of constant fidgeting in their seats, or of constant shifting from one leg to the other when forced to stand in one place. They prefer to keep moving and have less pain with walking than standing. The question "Can you sit comfortably through a movie?" is a very effective screening tool.

Physical examination findings are generally minimal, except for transverse lumbosacral tenderness, and occasionally paralumbar muscle spasm. Neurologic signs are typically absent. Straight leg raise is usually normal, except for hamstring tightness. Patients who have exquisite



Fig. 94.3: Lateral radiograph showing significant intervertebral collapse at the L5-S1 level with retrolisthesis of L5 on S1 and vacuum phenomenon within the disc space.

pain on extension may respond to facet blocks but generally are not improved beyond a short period of time.

Radiographic findings may include decreased disc height. Collapse with retrolisthesis of the cephalad vertebral body may be seen in more advanced cases (Fig. 94.3). True dynamic instability according to White and Panjabi's criteria¹⁴ is rare in purely degenerative cases, but significant retrolisthesis is indicative of failure of segmental stability. A vacuum phenomenon in a collapsed disc is a fairly reliable sign on plain radiographs that the degenerative segment can be mobilized at the time of anterior discectomy.

The magnetic resonance imaging (MRI) findings may vary from simple decreased signal on T2 sagittal images to protrusions, annular bulges and herniations to frank collapse with Modic changes on one or both endplates. One of the best uses of MRI is to evaluate the integrity and hydration of the adjacent lumbar discs in comparison to the degenerative disc or previously operated disc (Fig. 94.4). Pristine signal at all other levels with only a single collapsed disc space (with or without previous surgery) is a relatively straightforward diagnosis in a patient with disabling back pain who has failed conservative care.

A more difficult diagnostic scenario occurs when patients have typical symptoms, a negative neurologic examination, and have multiple discs with abnormal signal and varying degrees of degeneration. With the knowledge that 40% or more of the asymptomatic population may have abnormal disc signal on MRI,^{25,26} surgeons must identify the pain generator, which often requires further



Fig. 94.4: Sagittal T2-weighted magnetic resonance imaging showing a single-level degenerative disc with normal appearing discs otherwise. Patient had a positive discogram for concordant pain with morphological changes at the L4-L5 level. This patient is an excellent candidate for total disc replacement.



Fig. 94.5: Sagittal T1-weighted magnetic resonance imaging showing multiple degenerative levels of varying severity. This patient is not a candidate for surgical reconstruction.

investigation. Although the use of discography remains controversial in some regions, most surgeons who frequently operate on axial back pain feel that discography is an indispensable tool that should be used in the diagnostic algorithm. In the scenario of multiple degenerative discs at varying stages, discography can be the vital part of the equation, and often serves to guide therapeutic decision making.

An older patient with two-level disease on imaging, both causing significant concordant pain reproduction on discography, should not be offered a single-level reconstructive option with an expectation that surgery will be successful. Similarly, a younger patient with three or four anatomically abnormal and significantly painful lumbar discs is not a candidate for surgical reconstruction (Fig. 94.5). Three- and four-level operations on young patients will undoubtedly create long-term problems while they are still in their productive working years. These younger patients with multilevel disease should be advised to consider pain management options while technology and biologic research are advanced, with the hope of better treatment options for them in the future, rather than proceeding with bridge-burning procedures now.

Off-label uses of arthroplasty technology (multiple levels, hybrid constructs) are generally not approved by insurance carriers, so that clinical experience in the United States is limited to scattered small case series. Good clinical outcomes have been reported in the two-level

ProDisc-L IDE study;²⁷ however, the approval of two-level arthroplasty by the FDA has yet to be attained. Hybrid constructs have not been studied in any prospective level I studies to date.

One of the most exciting benefits of the IDE study data concerns the protective effect of arthroplasty on the adjacent level.⁹ Radiographic changes of decreased disc height, endplate sclerosis, osteophyte formation, and spondylolisthesis were found adjacent to single-level fusions three times more frequently than adjacent to arthroplasty implants at 5 years follow-up. These two patient cohorts were enrolled in the ProDisc-L versus 360° fusion FDA IDE study, and these comparisons were made between preoperative and 5-year postoperative radiographs. Assessments were done by independent radiologists, and the findings were highly statistically significant. This points to a clear advantage of arthroplasty in the treatment of single-level disc disease, and longer follow-up may correlate these radiographic findings with a decrease in the need for adjacent level surgery in the arthroplasty group.

Contraindications for disc arthroplasty have also been set forth by the IDE studies. As mentioned before, bone density is a necessary preoperative investigation. A T-score of < -1.0 is a contraindication to TDR. The presence of significant spondylolisthesis greater than grade I is also an absolute contraindication. Scoliotic curves $>11^\circ$ should not be offered a disc replacement at any level. The presence of current or past infection at the operative level, tumor, significant facet arthritic changes, excessive facet

removal from previous surgery and significant metal allergy are all impediments for arthroplasty. Any relative or absolute contraindication for anterior exposure of the lumbar spine for fusion should also be considered in deciding whether patients are arthroplasty candidates, including multiply operated upon abdomen, previous retroperitoneal approach, history of serious pelvic inflammatory disease, and significant atherosclerotic vessel disease in the abdominal vessels.

SURGICAL TECHNIQUE

The operating room setup maximizes the efficiency of the procedure. Use of a large operating room is recommended to accommodate personnel and equipment. The patient should be supine on the radiolucent operating room table positioned so that the base of the table does not interfere with the C-arm. Positioning of the access surgeon and primary surgeon is based on personal preference. The “French position” (surgeon between the patient’s abducted legs) technique is an alternative technique. The top of the iliac crest should be positioned in line with the “break” in the table, in order to hyperextend the lumbar region for better intraoperative visualization of the disc space. The plane of the pelvis is based on the position of the anterior superior iliac spines, and should be parallel to the floor. The arms should be padded and wrapped in front of the patient’s chest and out of the fluoroscopic field. The lower extremities should be in neutral position, with appropriate padding.

A paramedian, left-sided incision is preferred for the retroperitoneal approach. A right-sided approach for L5-S1 can be used in cases when the patient has lesser degree degenerative discs at L4-L5 or L3-L4, so the left retroperitoneal approach remains viable for a subsequent procedure. Following a retroperitoneal approach, retrograde ejaculation occurrence has been shown to be 10-fold less than after a transperitoneal approach.²⁸ Laparoscopic techniques have failed to prove beneficial.

The incision can be made vertical or horizontal for a one-level procedure, depending on the size of the patient. Usually a 6–8 cm paramedian, horizontal incision is used at the level of the disc space to be approached. In the case of larger patients, the vertical incision should be used to allow for a more extensile exposure (Fig. 94.6). Based on the relation of the L4-L5 disc space to the iliac crest on preoperative lateral radiographs, the incision should be situated caudal or cephalad on the abdomen to the level

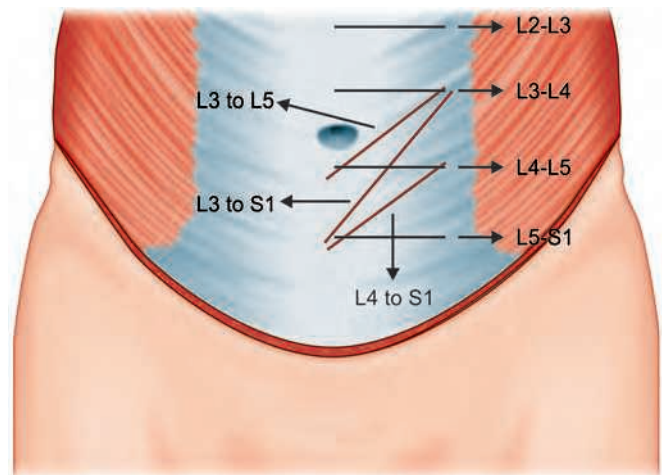


Fig. 94.6: Illustration showing potential abdominal incisions for the retroperitoneal approach to the different levels of the lumbar spine.

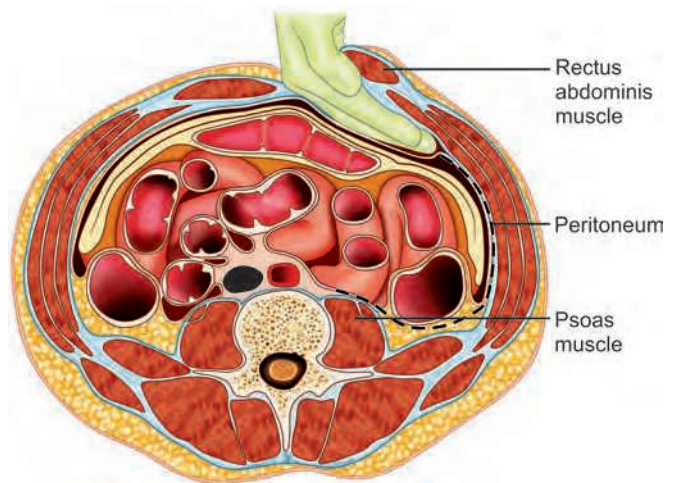


Fig. 94.7: Cross-sectional view showing the plane of dissection for the retroperitoneal approach to the lumbar spine.

of the iliac crest. The angle of the intended disc space can also be verified with a lateral fluoroscopic image.

Following the skin incision, bovie cauterization is used to dissect down to the anterior rectus fascia. The fascia is incised obliquely and the midline fascial raphe of the rectus should be identified. The left rectus is then mobilized to the left with careful attention to avoid injury to the inferior epigastric vessels. Blunt dissection is used to develop the plane superficial to the peritoneum. The plane is dissected on the left abdominal wall around the sigmoid colon and posterior toward the psoas muscle (Fig. 94.7). The entire peritoneum can be bluntly dissected and separated from

the abdominal wall. The ureter should be visualized to remain attached to the posterior peritoneum. Handheld retractors are used to retract the peritoneal contents from left to right. For L5-S1 approaches, the middle sacral artery (or arteries) must be dissected and ligated in the space between the common iliac veins overlying the disc space. For L4-L5 approaches, the ileolumbar vein (or veins) frequently tethers the iliac vein and can inhibit proper mobilization of the great vessels. If so, this vein must be identified prior to mobilization of the great vessels and ligated. Also, segmental arteries should be identified. They are rarely ligated for L4-L5 and L3-L4 single-level approaches.

Once the peritoneum has been successfully mobilized and the vascular structures protected, the intended disc space(s) must be verified with fluoroscopic imaging. Often there is inflammatory tissue anterior to the spine, making dissection and mobilization of the vascular structures tedious and more difficult. Either table-held retractors or handheld vein retractors can be used on each side of the spine to create a safe working environment.

Confirmation of the desired level and identification of midline are crucial. A bent spinal needle, a specialized marker, or a large-fragment screw can be used and placed into the disc space in the anticipated midline. Lateral fluoroscopic images are used to verify the disc level. With the spine in neutral rotation, an anteroposterior (AP) image is used to show the relation of the marker to the true midline. Landmarks such as the symmetry of the pedicles, the position of the vertebral body margins, and the midline position of the spinous process are used to verify midline. Cautery is then used to mark the midline on the adjacent anterior vertebral body or the placement of a specialized marker can also be used.

An anterior anulotomy centered on the midline mark is then completed using a long-handled knife, cutting away from retracted vessels. A Cobb elevator is then used to carefully dissect the plane between the disc material and the endplates. The majority of the disc can then be excised using a pituitary rongeur. With severely collapsed disc spaces, curettes are used to dissect into the disc space. Larger curettes are used to remove the cartilaginous endplate. Perforation of the endplate should be absolutely avoided in arthroplasty cases. The entire disc space should be cleaned of disc material and cartilage, leaving behind both lateral anulus and the posterior longitudinal ligament. For arthroplasty cases, meticulous discectomy in the posterolateral corners is also crucial for successful remobiliza-

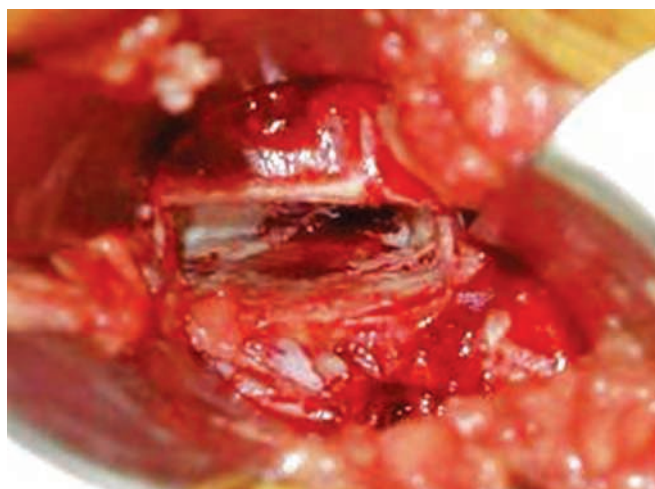


Fig. 94.8: Intraoperative picture showing a symmetric, completed discectomy

tion of the segment. The final discectomy should be symmetric (Fig. 94.8).

Restoration of the disc height is crucial in order to allow for a mobile segment. Often the disc space is significantly degenerative and collapsed, making it necessary to release constraining soft tissues. An angled curette within the disc space can be used to dissect the posterior longitudinal ligament (PLL) away from the vertebral bodies, which makes remobilization easier. Lateral fluoroscopic images should be utilized with the curette in place to aid in PLL dissection. In some cases, there is a posterior ledge of bone that may need to be removed in order to get the prosthesis posterior as possible. A curette or a Kerrison rongeur is often needed. In very collapsed disc spaces, the PLL may need complete resection to successfully mobilize the segment. Specialized distractors also aid in remobilization of the segment. Care must be taken to insert the distractors posterior in the disc space resting on the peripheral cortical ring, to avoid perforation of an endplate (Fig. 94.9).

Once remobilization of the disc space is completed, trial implants can be inserted into the disc space. For the Synthes ProDisc-L, a 10 mm trial is used at first, and increases in size are dependent upon the resistance encountered and the comparison to the relative disc height of the adjacent levels, as seen on the lateral fluoroscopic images. The trials should be centered on the previously made midline mark. Once the appropriate trial is placed, an AP image is taken to verify the position of the trial in relation to the midline. If the trial is translated off-center, further soft tissue releases or discectomy may be required to “balance” the disc space, allowing the trial to center.

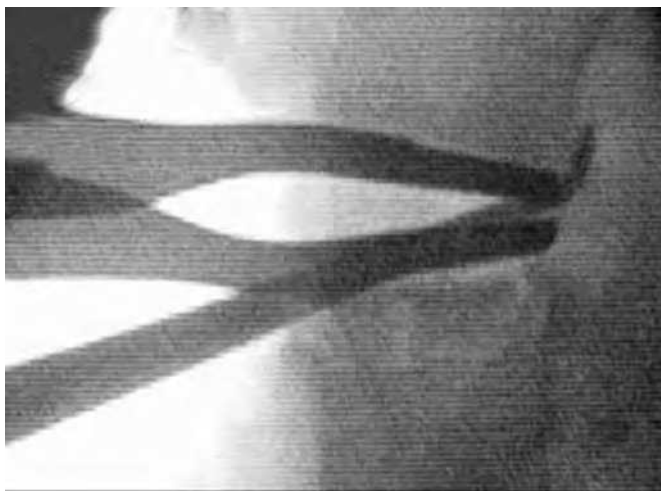


Fig. 94.9: Intraoperative lateral fluoroscopic image showing disc space distractor in correct position and curette dissection of posterior longitudinal ligament off the posterior vertebral body.

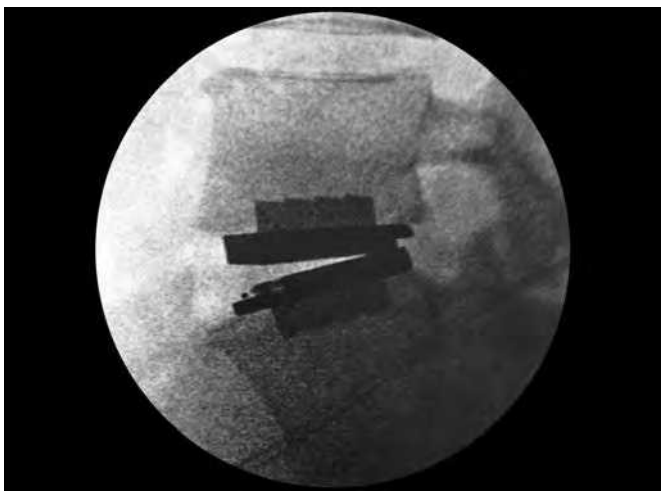


Fig. 94.10: Intraoperative lateral fluoroscopic image showing the correct position of the ProDisc-L implant at L4-L5 in relation to the posterior vertebral bodies.

Table 94.1: The varying sizes of available ProDisc-L implants.

Endplate footprint	Medium 34.5 × 27 (mm)	Large 39 × 30 mm
Superior endplate angulation	6°	11°
Polyethylene inlay thickness	10 mm, 12 mm, 14 mm	

At the time of this writing, the only FDA-approved device in the US market in the lumbar spine is the ProDisc-L. The size of the implant should be decided from the tactile feedback and fit of the trial component. There are several variations and combinations in width, depth and height for the ProDisc-L device (Table 94.1). The ProDisc-L device is a keeled device and therefore also requires preparation of the vertebral bodies for the keels. This is completed by using the appropriately sized chisel that is placed over the trial insertion stem and the chisel is impacted into the vertebral body under lateral fluoroscopic imaging. If the table has been hyperextended for disc space preparation, the angle should be returned to neutral before cutting the keel. After keel preparation, the disc space should be debrided of any remaining disc or cartilaginous debris.

The prosthesis can now be inserted along the keel tracts. Using steady, deliberate mallet blows, the prosthesis is inserted into the disc space along the keel tract under lateral fluoroscopic imaging. Lateral fluoroscopic images are used to verify the trajectory angle as well as the depth of the implant. Ideally, the device should be inserted as far posterior as possible into the disc space (Fig. 94.10). The

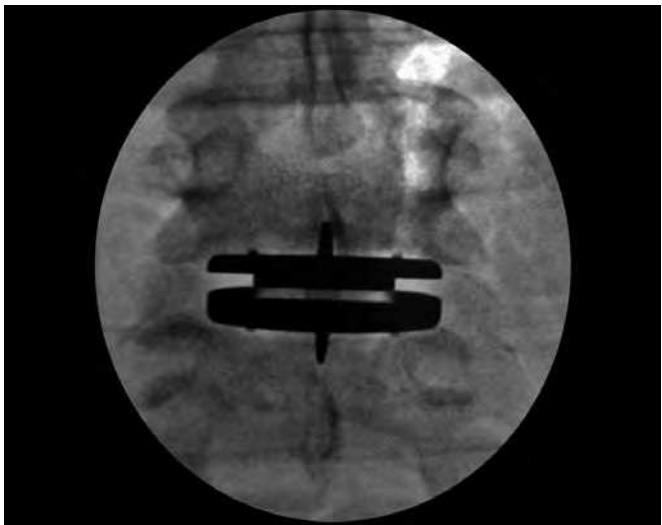


Fig. 94.11: Intraoperative anteroposterior fluoroscopic image showing correct position of the ProDisc-L implant at L4-L5. Note the relationship of the keels to the spinous processes and the symmetric position of the prosthesis in relation to the pedicles and the lateral vertebral body.

ProDisc-L polyethylene portion of the bearing surface is inserted last, between the two endplates. Proper insertion and locking of the polyethylene component must be verified. A final AP image should be taken to verify position of the prosthesis to be within the center of the disc space, using the anatomic landmarks mentioned before (Fig. 94.11). If the implant is off-center by a significant distance, the device may need repositioning and the keels

cut again. Finally, gross inspection of the implant and disc space should be done to verify there is no significant debris between the bearing surfaces and to verify proper assembly.

COMPLICATIONS

As with all spinal surgery, successful outcomes are dependent upon avoiding complications. Arthroplasty complications can be divided into three main categories: approach-related complications, technical complications and device-related complications.

Approach-Related Complications

The anterior retroperitoneal approach to the lumbar spine by a skilled access surgeon should be a minimally invasive technique. Through careful exposure and adequate retraction, complications can be minimized. Approach-related complications are similar for TDR and anterior fusion procedures. The most common complication encountered in anterior exposures is vascular injury—predominantly to the venous structures and very rarely an arterial injury. These injuries can be catastrophic without the experienced surgeon on hand for vascular repair. Direct injury or clot is found to occur <1% of cases.²⁹ Although some spinal surgeons are certainly adept at exposure of the anterior lumbar spine, a multidisciplinary approach using an access surgeon can be beneficial to address any approach-related complications that may occur.

With the advent of the less invasive retroperitoneal technique for exposure, retrograde ejaculation has been minimized from 13.3% (with the transperitoneal approach) to 1.7%.³⁰ Careful dissection of the hypogastric plexus up and off the vessels prior to retraction can aid in avoidance of this complication.

In the ProDisc IDE study at 5-year follow-up, the number of adverse events between the TDR group and the fusion group was not significantly different, including retrograde ejaculation.⁸ Severe, life-threatening events were found to occur significantly more often in the fusion group. No infections were reported in the TDR group, whereas the fusion group had two posterior wound infections. All deaths in the study were found to be unrelated to the surgical intervention. Other potential approach complications include ileus, thrombophlebitis, incisional hernia, warm feeling leg, nerve palsy, ureter injury, and bowel injury.

Technical Complications

Improper midline identification is the most common technical complication that can occur. During fluoroscopic verification of the midline, the surgeon must make a visible mark in the vertebral body or use a radio-opaque marker to aid in the remainder of the surgery. For accurate determination of midline, use of the lateral margin of the vertebral body as a reference is more reliable than using the spinous processes.³¹ Accurate midline identification is especially important with keeled prostheses because repositioning is much more difficult after an improper keel track has been cut into the vertebral body. Throughout the procedure, the surgeon should carefully perform discotomy symmetrically about the midline mark. If an un-keeled prosthesis is malpositioned in relation to the midline, removal, and repositioning are a must; however, keeled prostheses present a challenge for the surgeon because cutting a second keel introduces a significant risk of fracture between the two keels and creating a loose implant. There is no definitive study with recommendations about what is an acceptable intraoperative position. The goal should be to have the midline of the prosthesis to be within 3 mm of the vertebral midline on final AP fluoroscopic image. If the implant is too far off the midline, asymmetric loading of the endplate and facet joints can occur, which could lead to postoperative pain source.

Anterior-posterior placement of the device is also important for successful outcomes. In order to best recreate normal spinal segment motion, the prosthesis should be positioned as far posterior within the disc space as possible based on lateral fluoroscopic images. A posterior-placed device allows a more physiologic transfer of loads to the vertebral bodies and aids in unloading facet joints during lumbar extension.³² For the unconstrained device, the center of rotation more closely mimics that of the normal spinal segment, whereas in the constrained devices the center of rotation lies slightly anterior to that of physiologic motion.³³

Proper endplate preparation is paramount for avoiding complications. Improper trajectory with a curette or other instrument during endplate removal can lead to weakening of the support structure for the implant and possibly future subsidence and/or fracture of the endplate. If recognized intraoperatively, conversion to anterior fusion should be considered if the endplate violation is sizable.

Intraoperative fracture can occur, especially fracture of the posterior vertebral bony edge on the cephalic vertebral body. Usually, this is a result of inadequate posterior release of the anulus and posterior longitudinal ligament.

Sometimes the posterior bony edge needs to be removed in order to obtain a better position of the prosthesis and also to avoid fracturing the posterior vertebral lip during trialing or implant insertion.

Subsidence can also be caused by undersizing the prosthesis, where the edge of the prosthesis rests on the concave portion of the vertebral body instead of the strong apophyseal ring. Conversely, oversizing the implant may result in dislocation of the device.

Preoperatively unrecognized osteopenia or osteoporosis can place all prostheses at risk for early postoperative subsidence and failure, regardless of size and position. Preoperative bone density scans aid in proper patient selection, even in male patients. A T-score of > -1.0 is required for arthroplasty patients.

Device-Related Complications

Longevity of artificial disc replacements may be threatened by intrinsic factors, such as wear debris and its consequences. Through retrieval studies, it has been shown that both unconstrained and constrained implants have characteristic patterns of wear. With the unconstrained design, adhesive and abrasive wear occurred in the domed portion of the polyethylene core as well as chronic rim impingement, resulting in fracture of the core in some patients.^{34,35} The constrained devices show posterior burnishing/impingement of the metal endplates, backside wear of the polyethylene and evidence of third-body wear.³⁶ Once wear debris accumulates about a prosthesis, the long-term effects on the adjacent osseous anatomy may potentially lead to osteolysis and subsequent implant subsidence. The osteolysis is theorized to be caused by particle-induced activation and exhaustion of macrophages. This creates a proinflammation environment about the prosthesis, with the cytokine production affecting rates of cellular death, osteoclast population, and activity.³⁷ Unfortunately, the understanding of how to minimize wear debris is incomplete; however, the overall incidence of significant osteolysis at the present time is extremely low. Long-term follow-up will provide more answers as to effects wear has on clinical outcomes. Furthermore, newer design concepts such as the plasma discs may prove to eliminate the concern for wear debris.

POSTOPERATIVE CARE

Immediate postoperative care of the TDR patient is much the same as an anterior lumbar fusion. The risks of postope-

rative ileus, deep vein thrombosis, and wound infection are similar.^{3-6,8} Early mobilization and ambulation are paramount for TDR patients—it should be encouraged immediately, the day of surgery. Gentle abdominal flexion exercises can also be started the day of surgery. There is no necessity for formal brace immobilization unless there is a concern for intraoperative iatrogenic fracture. A light corset brace or abdominal binder can be instituted for comfort in the first week postoperatively, and this also helps avoid peak loading of the implant that occurs in extreme positions. After hospital discharge, patients should be instructed to avoid strenuous activity and motions that peak load the implant, particularly lumbar extension. These restrictions should be in place for up to 3 months.

During the first 6 weeks, walking and light lower extremity strengthening exercises are allowed. Core exercise should be avoided until adequate time has been allotted for the abdominal musculature to heal from the surgical approach. Between 2 and 6 weeks postoperatively, patients can be enrolled in an organized physical rehabilitation program focusing on trunk stabilization and lower extremity strengthening.³⁸ Lumbar extension is generally avoided in the first 3 months to allow adequate time for bony ingrowth at the implant-endplate interface. Return to sporting activity can be allowed in the first 3–6 months postoperatively, depending on the patient's progress and the type of sporting activity. There is no consensus as to restricting particular sporting activities. The only study to date on return to sporting participation after TDR shows patients are able to return to high-level competitive sports, professional athletics as well as extreme sports, with peak performance being attained on average at 5.2 months postoperatively.³⁹

Return to work should be made on a case-by-case basis. Depending on the rigors of a particular working environment, some patients can return to work within the first few weeks if their job entails mostly sedentary duties. Other patients whose careers involve more strenuous activities, such as firefighters or heavy laborers, should postpone their return to work until a minimum of 3 months has passed, and may then be evaluated according to their level of rehabilitation. No long-term restrictions are generally required for the TDR implant itself.

Evaluation of the TDR patient should be ongoing. Clinical and radiographic follow-up appointments should be set at 2 weeks, 6 weeks, 3 months, 6 months, 12 months, and annually thereafter to assess the viability of the implant and to screen for osteolysis.

DISCUSSION

Outcomes Data

Over the past decade, there has been a distinct transition in the spine surgery literature toward utilizing the best evidence possible for recommending treatment options. Level of evidence was first introduced to the *Journal of Bone and Joint Surgery* in 2003, with Level I evidence being considered the highest level for a clinical study.⁴⁰ Approximately 16% of spine studies published are considered Level I evidence.⁴¹ Level I studies are defined as being well-designed randomized controlled trials (RCT) with standardized randomization and >80% follow-up, which includes FDA IDE studies of arthroplasty.^{3-5,42}

The early literature on disc arthroplasty consisted predominately of European case series reports. Although not Level I studies, they definitely provided valuable information. The initial experience published by Griffith et al.⁴³ showed statistically significant pain relief in patients implanted with the Charité at nearly 1 year follow-up. The early failure rates were found to be 6.5%. Other positive clinical results of the study also included improvements in walking distance, overall lumbar mobility and even neurologic improvements after disc arthroplasty. A 10-year follow-up study on Charité patients provided continued momentum for the procedure.⁴⁴ This study presented 90% excellent or good clinical outcomes with a return to work rate of >90% in 100 patients. Analyzing the radiographic outcomes, they found a mean flexion/extension range of motion of 10.3°. Other long-term studies from European centers also showed similar success rates with the Charité prosthesis. In 2007, David⁴⁵ published results of 106 patients followed for a mean of 13.2 years. Again, the success rate was high (82% excellent to good) and nearly a 90% return to work, including a return to work of >75% of the heavy laborers. The long-term device-related complication rate was <5%.

Unfortunately, these early studies were only considered fair levels of evidence and they failed to use validated outcomes measures. The US IDE studies on the Charité and ProDisc-L were introduced in the early 2000s and set out to prospectively investigate arthroplasty using a randomized controlled design with validated outcome measures.

The Charité study used a 2:1 randomization ratio with a total of 304 patients—205 investigational patients and 99 in the control group treated with stand-alone ALIF with BAK fusion cages.³ This was a multicenter endeavor with

Table 94.2: Clinical success rates reported in the Charité and ProDisc-L FDA IDE trials at 2-year and 5-year follow-up.

	Success 2 years	Success 5 years
Charité	63.6%	57.8%
ALIF control group	56.8%	51.2%
ProDisc-L	53.4%	48.1%
360 fusion control group	40.8%	41.1%

(IDE: Investigational device exemption).

The results of the two studies cannot be compared or combined as different definitions of success were used.

14 original sites participating in the 2-year study and 8 sites agreeing to participate in a second study following the original patients for 5 years.⁶ Overall success was defined by patients who satisfied all of the following criteria: (1) improvement in ODI by at least 15 points, (2) no device failure requiring an additional surgery, (3) absence of significant complication, and (4) maintained or improved neurologic status over the follow-up. Other secondary measures included VAS pain intensity, SF-36, work status, patient satisfaction, and radiographic data such as ROM. Both the 2- and 5-year Charité studies showed noninferiority to the fusion controls in regard to overall success (Table 94.2). Secondary measures also showed statistically significant improvement in ODI values, VAS pain scores and SF-36 physical component scores for both groups with no statistically significant differences between the groups (Table 94.3). Also, and possibly more important, the rates of patients with full-time employment were higher in the Charité patients (65.6%) compared to the fusion controls (46.5%), which reached statistical significance ($p < 0.05$). Failure rates for the fusion cohorts were twice that of the Charité patients (16.3% vs. 7.8%). All failures in the fusion group were related to pseudarthrosis and they occurred within the first 2 years. Five of the seven Charité failures were found within the first 2 years. Six of these seven failures in the Charité group went on to have posterior instrumentation and fusion for various reasons.

One criticism of the Charité study involved the use of an ALIF with BAK cages as the control arm. However, this was one of the few FDA-approved devices of this type at the time the study was designed. Also, it provided a technique more similar to the TDR procedure in that no additional posterior approach was required. A different control group was selected in the ProDisc-L IDE study.⁸ The control arm for these results was circumferential lumbar fusion using femoral ring allograft and posterior iliac crest autograft

Table 94.3: Secondary measures also showed statistically significant improvement for both TDR and fusion groups at 2-year and 5-year follow-up, with no statistically significant differences between the groups (values for the studies cannot be compared or combined as different versions of VAS and ODI were used).

	<i>Charité</i>	<i>ALIF</i>	<i>ProDisc</i>	<i>360 fusion</i>
VAS pain score				
Pre-op	69.7	70.4	75.9	74.9
2 years	27.2	32.8	36.6	43.3
5 years	31.1	29.1	37.1	40.0
ODI				
Pre-op	48.0	51.1	63.4	62.7
2 years	21.8	27.0	34.5	39.8
5 years	24.0	23.6	34.2	36.2
SF-36 physical				
Pre-op	Not reported	Not reported	31.1	30.9
2 years	Improved 14.2 points from pre-op	Improved 11.2 points from pre-op	42.8	38.8
5 years	Improved 12.6 points from pre-op	Improved 12.3 points from pre-op	42.0	40.1

(VAS: Visual analog scale; ODI: Oswestry disability index; ALIF: Anterior lumbar interbody fusion; TDR: Total disc replacement).

Table 94.4: Clinical success parameters for the ProDisc-L IDE.

<i>Parameter</i>	<i>Criteria</i>
ODI*	>15% improvement compared to baseline value
Device success	No reoperation for device removal or revision and no addition of supplemental fixation
Neurological success	Maintenance or improvement in each evaluation: sensory, motor, reflex, and straight leg raise
SF-36	Any improvement in the physical and mental components composite score compared to baseline values
Radiographic success	No device migration
	No subsidence
	No radiolucency
	No loss of disc height
	Fusion status
	Range of motion: measured from flexion/extension radiographs and restored to within normal range of motion defined to be 6–20° at L3-4 and L4-5; and between 5° and 20° for L5-S1

(ODI: Oswestry disability index; IDE: Investigational device exemption).

*Data also analyzed based on suggested FDA criteria of a minimum 15-point improvement in ODI scores.

A patient had to fulfill all of the criteria to be considered a success.

supplemented with pedicle screws. This Level I study randomized 236 patients in a 2:1 ratio. Clinical success was again the primary outcome measure, utilizing four clinical parameters and seven radiographic parameters (Table 94.4). In the 2-year arm, the ProDisc-L patients showed a statistically significant greater rate of clinical success compared to the 360 fusion controls (54.3% vs. 40.8%; $p < 0.05$). Arthroplasty was found to be superior or at least similar to fusion in all secondary outcome measures. This trend was

maintained in the 5-year follow-up, involving all investigational sites and their patients, with the TDR group having a success rate of 53.7% and the fusion cohorts having 50.0% success rate (with >80% follow-up rates). Patient satisfaction was high in both groups at 5 years, with more patients in the TDR group than the fusion group stating they would have the surgery again. Reoperation rates were higher in the fusion group than the TDR group (12% vs. 8% respectively).

Another noteworthy IDE trial with 2-year published results involved the Maverick device, which is not currently commercially available in the United States at the time of this writing.⁵ This was also a randomized, prospective trial comparing TDR and stand-alone ALIF using metallic cages and bone morphogenetic protein as a graft substitute (rhBMP-2). The study was designed to show superiority of the TDR device rather than noninferiority as with the Charité and ProDisc-L trials. Larger numbers of patients were enrolled as compared to the other IDE studies (405 TDR and 172 controls). Overall success for this trial was defined as ODI improvement >15 points, no worsening of neurologic status, maintenance of disc height, no reoperation, and absence of significant device- or surgery-related complication. The TDR group was found to have statistically superior results compared with the control group in regard to the overall success and all secondary outcome measures. The TDR cohorts were also found to have significantly fewer device- and surgery-related adverse events ($p<0.05$).

There are several other ongoing IDE trials in the United States involving lumbar TDR at varying stages of follow-up. To date, no FDA IDE study on arthroplasty has found the devices to be inferior to fusion or have comparably unacceptable failure rates.

Range of Motion

Radiographic outcomes regarding range of motion after arthroplasty are also a significant discussion point. The longest series of TDR patients shows range of motion in flexion/extension to be on average 10.1° and lateral bending 4.4° at the operative level with mean follow up 13.2 years.⁴⁵ Level I data from the FDA IDE Charité study also show maintenance or improvement of the ROM at the operative level compared to a substantial decrease in the ROM of the fusion segments.⁴⁶ Cadaveric analysis has also shown that spinal motion is similar between intact spines and those implanted with TDR at a single level.²³ Other clinical studies also have shown that the range of motion of adjacent discs was less altered after TDR compared to fusion, in which the TDR level only accounted for a slight loss in total ROM of the lumbar spine, whereas after fusion every level compensated for the loss in motion (mostly at the first cranial adjacent level).⁴⁷

In regard to clinical outcomes, the resultant ROM after TDR has also been linked to better outcome measures. Huang et al.⁴⁸ showed better clinical outcomes in

patients with TDR that maintained at least 5° of implant F/E motion at 8.6 years mean follow-up.⁴⁸ Mid-term 5-year radiographic data from the ProDisc IDE study show the prostheses maintain ROM at the index level with a mean of 7.2°.⁸ Longer-term data is necessary to draw a final conclusion; however, it appears that TDR can maintain adequate ROM at the operative level over time and the better the motion, the better the clinical outcomes may be.

Adjacent Level Disease

A second important measure of clinical outcome is ASD rates after fusion and arthroplasty. Although much of the literature on ASD after fusions has largely been Level II or III evidence, it provides historical controls for the expected rate of ASD after fusion. In a level III study, Ghiselli et al.⁴⁹ determined the rate of symptomatic ASD after fusion to be 16% at 5 years and 36.1% at 10 years. The only prospective study concerning ASD after fusion shows a 10-year rate of ASD to be 38%.⁵⁰

Adjacent segment degeneration after TDR has been found to be less than that of fusion, likely due to a reduction in the transmission of forces to the adjacent segment, which is supported by cadaveric and finite element analyses showing a distinct advantage of TDR over fusion in maintaining normal kinematics of the adjacent disc and facet joints.^{21-23,51} Clinically, the aforementioned long-term level III study on TDR has shown ASD to be <3% at 13 years follow-up.⁴⁵ Based on level I data, TDR has more recently been shown to have statistically significantly lower rates of radiographic changes at the adjacent segment compared to baseline at 5-year follow-up, upward of a threefold difference.⁸ This 5-year IDE data also showed adjacent level surgery rates to be 2% for TDR and 4% for fusion patients. The mid-term results show less severe changes at the adjacent level after TDR compared to fusion, but further long-term comparisons will be needed to prove this definitively translates to a clinical benefit of TDR.

Two-Level Arthroplasty

At the time of this writing, two-level TDR is not yet approved by the FDA. The only current level I study published on multilevel arthroplasty compared two-level TDR with the ProDisc-L device to two-level circumferential arthrodesis in a 2:1 randomization trial.²⁷ The clinical success was based on the parameters previously mentioned for the single-level IDE study. Similar to the single-level study, patients in the TDR group had better outcomes in regard

to multiple measures—ODI, SF-36, and VAS pain levels. Clinical success was obtained in 73.2% of the arthroplasty patients and 59.7% of the fusion patients. Based on these results, noninferiority of two-level arthroplasty was concluded. Although FDA approval may occur based on the 2-year and longer data, insurance coverage will likely remain an issue even if FDA approval is obtained for the procedure.

Economic Impact

Finally, it is important to discuss the economic implications of TDR. The most appropriate outcome-based control for clinical comparison studies is a circumferential arthrodesis utilizing the anterior interbody technique. For anterior spinal fusion, the use of rhBMP-2 significantly alters the hospital costs; therefore, it is difficult to directly compare procedures. At many institutions, the use of rhBMP-2 in anterior lumbar fusions has been exceedingly more common. In general, TDR costs are similar to circumferential fusion (utilizing either anterior inter body or transverse inter body technique) without the use of rhBMP-2.¹² Accounting for the cost of rhBMP-2, TDR is considerably less expensive than anterior/posterior fusion. In comparing one- and two-level TDR to circumferential fusions, Levin et al.¹⁰ found that for the one-level comparison there was a significant difference in charges, with the fusion costing >50% more in operating room charges than TDR. The two-level comparison showed similar total charges between the groups. An economic model comparing both hospital costs and third-party payer costs for arthroplasty and three different types of fusion also showed that the overall economic effect of single-level arthroplasty is equal if not less than a fusion.¹¹

CONCLUSION

Lumbar arthroplasty may prove to be one of the more significant advances in the surgical treatment of functionally disabling degenerative disease of the lumbar spine. In an ideal future scenario, we will have noninvasive diagnostic metrics to differentiate between painless and painful degenerative discs, minimally invasive biologic interventions for early and intermediate phases of degeneration that can biochemically reverse the process and physiologic disc replacement implants for more advanced degenerative discs that have sustained irreversible structural damage; however, the science is not there yet for any of these three stages. Research is ongoing in diagnostic analysis of the chemical

products of disc metabolism either through harvest by a needle aspiration or by quantifying signal change on MRI. Future research should find other noninvasive means of identifying patients who would benefit from nonsurgical and surgical intervention. Currently, there are multiple research paths all aimed toward earlier intervention with biologic treatment. On the surgical front, several next-generation arthroplasty implants are being developed with shock absorption and viscoelastic response designed into materials and designs.

Through examination of the highest levels of current evidence in the literature, we can conclude that current arthroplasty designs are viable and have performed similarly to, if not better than, lumbar fusion. The implants are proven safe, with a lower reoperation rate than fusions. In regard to adjacent level degeneration, both in vivo and in vitro studies show that arthroplasty provides a protective benefit for the adjacent intervertebral disc level. The “perfect disc” is evolving from multiple ongoing clinical trials, and arthroplasty has proved itself worthy of continued clinical use.

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Cervical Disc Replacement

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Snapshot

- » Biomechanics of Arthroplasty
- » Indications for Arthroplasty
- » Preoperative Evaluation
- » Surgical Technique
- » Outcomes
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INTRODUCTION

Patients with cervical radiculopathy who are refractory to an adequate course of nonoperative therapy or have progressive neurologic deficits can be treated surgically. Decompressive surgery in these symptomatic patients can be completed successfully via an anterior or posterior approach.

An anterior surgical approach with anterior cervical discectomy and fusion (ACDF) is often preferred for patients with central and paracentral disc herniations or ventral thecal sac compression from osteophytes. The goals of ACDF are to decompress the neural elements, provide permanent segment stabilization, restore cervical lordosis, and preserve anatomical disc space height. However, the kinematics at levels adjacent to a fusion are altered and it is postulated that these changes may lead to an increased risk of adjacent-segment degeneration.

Cervical disc arthroplasty achieves adequate anterior decompression of the neural elements and also allows for preservation of physiologic motion patterns following surgery. This additional benefit compared to ACDF may reduce the incidence of degenerative disc disease at adjacent cervical motion segments following anterior cervical decompressive surgery.

BIOMECHANICS OF ARTHROPLASTY

For more than half a century, degenerative cervical spondylosis has been addressed from an anterior surgical

approach.¹⁻³ With refined operative techniques and modern implants, fusion rates following single-level ACDF have surpassed 95%.⁴ Several widely publicized, long-term follow-up studies, however, have raised concern regarding the rate at which these patients developed adjacent segment degeneration. One study reported that the incidence of *radiographic* adjacent segment degeneration was as high as 92% within 5 years of anterior cervical arthrodesis.⁵ Hilibrand presented data demonstrating that >20% of patients who underwent ACDF developed *symptomatic* adjacent level degeneration within 10 years of their index operation.⁶

The debate is ongoing, however, as to whether this patient population is naturally predisposed to adjacent level degeneration or whether the fusion actually promotes the accelerated degeneration. Several biomechanical, cadaveric models lend credence to those who espouse the latter.^{7,8} These and other studies have documented that rigid fixation across a previously mobile segment increases the shear stress across the adjacent disc spaces and causes elevations in intradiscal pressures—both phenomena that could promote degeneration at the adjacent level.^{9,10} Other well-designed biomechanical models have suggested that intradiscal pressure is not affected at adjacent levels or is only accelerated to a statistically significant degree following two- and three-level ACDF.^{11,12} However, others suggest that intradiscal pressure and range of motion at adjacent levels are unaltered by anterior cervical fusion, instead proposing that adjacent segment pathology should

represent the natural history and progression of cervical spondylosis.¹³ There are studies in the surgical literature as well that evaluate evidence from prospective clinical trials that compare arthroplasty with traditional ACDF. These studies conclude that maintaining cervical segmental mobility not only reduces radiographic evidence of adjacent level degeneration, but also decreases the incidence of symptomatic adjacent segment disease.¹⁴⁻¹⁹

Regardless, the universal objective of minimizing adjacent segment disease has provided the industrial impetus to develop motion-sparing implants and alternatives to fusion. Although a number of implants produced by various manufacturers are currently available, the underlying objective of each design remains constant—to serve as a fixed, interbody spacer that preserves cervical segmental motion and approximates anatomic alignment through a full range of motion.²⁰ Discussion regarding design details such as devices engineered to limit translation in certain planes or to optimize the center of rotation across the arthroplasty is beyond the scope of this chapter. Until prospectively collected data demonstrate statistically significant differences in outcomes across arthroplasty devices, the choice of implant will remain largely up to the surgeon's discretion. As discussed below, however, certain devices are manufactured from materials that may preclude imaging with cervical magnetic resonance imaging (MRI), and this may dictate which device is selected for implantation.

INDICATIONS FOR ARTHROPLASTY

Cervical arthroplasty is used as a motion-sparing alternative to ACDF for the treatment of single- or two-level degenerative disc disease or when adjacent to a prior ACDF causing a refractory radiculopathy or early spondylotic myelopathy between levels C3-4 and C7-T1.²¹⁻²⁴ At this time specific cervical arthroplasty devices are approved for single- and two-level degenerative disc disease of the subaxial cervical spine in patients who have failed at least 6 weeks of conservative therapy.^{23,25,26}

As one of the primary objectives of the artificial disc is its ability to preserve motion, patients with incompetent posterior elements are typically excluded from consideration of a motion-sparing approach as the facets are not replaced with the arthroplasty procedure. Therefore, patients with congenital, degenerative, iatrogenic, or traumatic facet defects are not ideal candidates for arthroplasty.²⁷ Otherwise, absolute contraindications to artificial disc implantation are few, but include cervical kyphotic deformity, active discitis or osteomyelitis, and radiographic instability

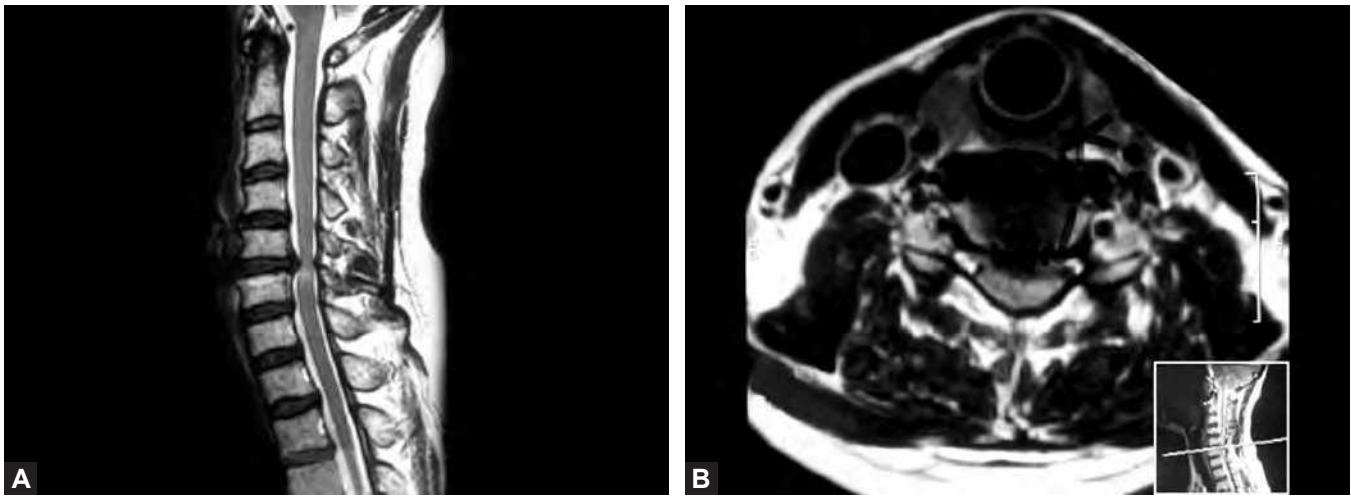
on dynamic cervical films.²⁸ Most trials considered age >60 years, uncontrolled diabetes, a history of rheumatoid arthritis, chronic steroid use, renal insufficiency, osteoporosis, active malignancy, or other metabolic conditions with poor bone quality relative contraindications to arthroplasty.^{15,17,23,29-31} The Food and Drug Administration (FDA) investigational device exemption (IDE) arthroplasty studies also excluded patients with evidence of severe spondylosis → 50% loss of disc height, bridging osteophytes, and <2° of motion—at the surgical level.^{15,29,30,32} Arthroplasty, particularly with stainless steel implants, should also be avoided in patients with conditions such as cervical syringomyelia or other pathologic conditions that require periodic surveillance MRI since the arthroplasty materials often create shadow artifact on MRI.

Ideal candidates for cervical disc arthroplasty are younger patients with good bone quality and no evidence of facet joint arthropathy or instability.

PREOPERATIVE EVALUATION

Symptoms of degenerative cervical disc disease may range from neck pain alone to pain in a particular dermatomal distribution or from paresthesias in the upper extremities to deterioration reported in dexterity or handwriting.^{25,26,33} A thorough neurological examinations of patients with these symptoms should include motor, sensory, and reflex examination. Ideal candidates for cervical discectomy are those patients with objective signs and/or clinical symptoms of cervical spinal radiculopathy or mild myelopathy. Myotomal weakness, sensory deficits, and diminished reflexes are objective clinical findings of radiculopathy.³⁴⁻³⁶ More diffuse weakness, hyper-reflexia, the presence of pathologic reflexes (i.e. Hoffman's sign, clonus), urinary retention, and gait instability are all objective findings suggestive of cervical myelopathy.³⁷ Given the widespread availability and noninvasive nature of MRI, many of the patients referred for cervical spine evaluation will have already undergone this study (Figs. 95.1A and B). Computed tomography (CT) myelogram has been relegated for use predominantly in situations where a patient is unable to undergo (e.g. the presence of a pacemaker or implantable cardioverter defibrillator) or to tolerate (e.g. claustrophobia, morbid obesity) an MRI.

Once a patient is diagnosed with compressive cervical pathology amenable to surgical intervention from an anterior approach, the spine surgeon must then determine whether the patient is a candidate for arthroplasty. Although not required, some surgeons also obtain CT



Figs. 95.1A and B: Preoperative magnetic resonance imaging (MRI) cervical spine (sagittal T2-weighted image) reveals a disc herniation at C5-C6 causing cord compression. Note evidence of T2 signal change within the cervical spinal cord at this level. (B) Preoperative MRI cervical spine (axial T2-weighted image) reveals cord compression from a central disc herniation at C5-C6.



Fig. 95.2: Preoperative dynamic lateral radiographs reveal no evidence of instability on flexion and extension.

scans of the cervical spine prior to artificial disc replacement to evaluate the integrity of the bony elements, to identify potentially cumbersome anterior osteophytes, and to document the absence of significant facet hypertrophy. In our practice, dynamic cervical radiographs in neutral, flexion, and extension are also obtained not only to review the individual patient's anatomic cervical alignment in the presence of an axial load, but also to identify kyphotic deformities or sagittal translation/instability >3.5 mm, which precludes an arthroplasty (Fig. 95.2). Electromyography (EMG) plays a limited role in the diagnosis of cervical radiculomyelopathy and does not guide the surgeon

in differentiating those patients who may benefit from arthroplasty versus a standard ACDF.³⁸⁻⁴¹

SURGICAL TECHNIQUE

The cervical arthroplasty technique is somewhat similar to an ACDF but several important differences need to be highlighted. Before surgery, the anteroposterior dimensions and the disc space height of the involved segment should be radiographically measured to determine the proper implant size.

A standard approach to the anterior cervical spine is undertaken. A transverse skin incision is made over the target interspace. Dissection is carried out medial to the carotid sheath and lateral to the trachea and esophagus to arrive at the anterior cervical spine. The omohyoid muscle is divided, if necessary in order to improve retraction.

Next, the level of the disc space is confirmed using fluoroscopy. The longus colli muscles are elevated subperiosteally off the lateral margins of the disc space and self-retaining retractors are placed. The anterior longitudinal ligament is also removed but dissection is not extended past the mid-portion of the vertebral bodies adjacent to the disc space. Gentle intervertebral distraction may be performed using vertebral body pin distraction with the goal of maintaining anatomical disc space height.

An incision is made in the anterior annulus fibrosus and the disc material is removed using pituitary rongeurs and curettes. The cartilaginous endplates are removed using curettes and the lateral margins of the disc space



Fig. 95.3: Postoperative anteroposterior image shows placement of the cervical arthroplasty device in the midline of the index level.

are exposed. It is important to preserve the bony endplate integrity. Hypertrophied uncovertebral joints are thinned with a high-speed burr and the neural foramina are enlarged using a thin-footed Kerrison. The posterior annulus and the posterior longitudinal ligament are removed with Kerrison and curettes. The central spinal canal and neural foramina are decompressed. The depth of the vertebral body is precisely measured using a caliper. Selection of the implant size is based on the approximate depth and height of the interspace. Special attention is given to not over-distract the interspace or oversize the prosthesis, as supra-physiologic disc space distraction will likely prevent anatomical segmental motion. The implant is positioned and fit into the center of the interspace and may be additionally secured to the adjacent vertebral bodies with screws (Fig. 95.3) or rails depending on the implant's design.

On a technical note, exquisite hemostasis is important to the long-term functional maintenance of the arthroplasty procedure. Using bone wax or a flowable gel foam with thrombin, all posterior osteophyte resection areas should be treated to prevent hematoma formation prior to placement of the prosthesis. Similarly, once proper placement of the implant is achieved, hemostasis of the anterior bony surfaces must be obtained to avoid both retropharyngeal hematoma in the acute postoperative period and heterotopic ossification in the long term. The formation of even a small amount of hematoma at a retained ligament near the disc space may act as a nidus for calcification formation and subsequent heterotopic ossification development.

OUTCOMES

The follow-up reports of cervical arthroplasty are not as lengthy as outcome reports for ACDF, which have more than two decades of follow-up.⁴² Still, the promising results of several FDA IDE arthroplasty trials prompted the North American Spine Society (NASS) in 2010 to state, "ACDF and total disc arthroplasty (TDA) are suggested as comparable treatments, resulting in similarly successful short term outcomes, for single-level degenerative cervical radiculopathy."⁴³ More recent findings suggest that even this guidance may be conservative as the superiority of arthroplasty over ACDF on many primary outcome measures is found when pooling the (largely homogeneous) data from several FDA IDE trial results.¹⁹

There are several prospective, randomized, multicenter US FDA IDE trials with results data ranging from 2 to 5 years, each comparing validated outcome measures—neck disability index (NDI), visual analogue scale (VAS) neck and arm pain, Short Form (36) Health Survey (SF-36), adjacent segment disease, repeat operation, range of motion, and adverse events—of a variety of artificial disc implants to standard ACDF.^{15,17,24,29,30,32,44} All of the US FDA IDE protocols published so far compared single-level artificial disc replacement to single-level ACDF.

In 2009, Murray et al. published the results of a prospective, randomized trial evaluating the ProDisc-C (Depuy Synthes Companies, Raynham, MA) across 13 centers.³² At 2-year follow-up, all 209 patients enrolled in the trial reported improvement in their NDI, VAS, and SF-36 scores with approximately 90% of patients reporting sustained improvement in their neurologic symptoms. The authors documented, however, a statistically significant reduction in the number of subsequent operations and in the quantity of pharmacologic agents prescribed to the 103 patients who underwent ProDisc-C implantation. This led the investigators to conclude that outcomes derived from implantation of the ProDisc-C device were at least equivalent to ACDF.

Phillips et al. in 2013 reported the results of a prospective, randomized, controlled investigation of the Porous Coated Motion (PCM) Cervical Disc (NuVasive, Inc., San Diego, CA).²⁴ In this study, 342 patients were enrolled (189 randomized to PCM, 153 to ACDF) and followed 2 years postoperatively as part of the device's US FDA IDE clinical trial. In contrast to other cervical disc arthroplasty devices, enrollment in the trial and subsequent FDA

labeling allowed for treatment of degenerated levels with PCM adjacent to prior ACDFs. Radiographic findings at 2 years showed a mean range of motion of 5.7° for the PCM and 0.8° for the ACDF group. Significant improvements in clinical outcomes were seen in both groups. However, NDI, dysphagia scores, patient satisfaction, and overall success (a composite endpoint including minimum 20% NDI improvement, no major complications, no neurologic worsening, no secondary surgical procedures, and meeting radiographic criteria of motion) were all statistically significantly improved for PCM compared to ACDF (all $P < 0.05$). The final comparison of overall success resulted in a superiority finding (rather than noninferiority) for PCM compared to ACDF (75.1% vs. 64.9%, respectively). When examining the subgroup of patients from each randomization who had undergone a previous ACDF, the findings were similar to the overall findings, though with attenuated clinical improvements in each group (PCM and ACDF).

Another multicenter, prospective, randomized trial that implemented an FDA IDE approved protocol was the Kineflex C (SpinalMotion, Mountainview, CA) trial.³⁰ In this trial, Coric et al. demonstrated noninferiority of artificial disc replacement compared to ACDF to treat single-level cervical spondylosis. At 24 months follow-up, the vast majority of all 269 patients reported significant and sustained improvement in NDI and VAS scores, and although there was a statistically significant increased incidence of radiographic adjacent segment degeneration among the ACDF group, there was no statistically significant difference in the rate of adjacent-level operation or repeat index-level operation.

By contrast, Sasso et al. reported that at 4 years, the outcomes of patients who underwent single-level arthroplasty with the Bryan Cervical Disc (Medtronic Spinal and Biologics, Memphis, TN) were statistically superior to those randomized to standard anterior cervical fusion with allograft and plate stabilization.⁴⁴ These findings reiterated the conclusion previously published by Heller et al. documenting the initial, 24-month outcomes data from the Bryan Cervical Disc trial.²⁹ Presenting clinical follow-up data on 319 prospectively randomized patients, Sasso et al. found that those patients who underwent arthroplasty had sustained statistically superior outcomes across virtually all validated outcome measures at 4 years, and while adjacent-segment degeneration was not specifically addressed, the rate of secondary surgical procedures at the index level was $<5\%$ in both groups.



Fig. 95.4: Postoperative dynamic lateral radiographs demonstrate the range of motion is maintained at the C5-C6 level.

In 2010, Burkus et al. published results of the largest FDA IDE arthroplasty trial, which enrolled >500 patients across 32 investigational sites who were followed for 5 years following either single-level Prestige ST Cervical Disc arthroplasty (Medtronic SofamorDanek Memphis, TN) or standard ACDF.^{17,38} This manuscript similarly served as an update to previously published 2-year outcomes data by the same investigators.¹⁵ Statistically significant improvements in NDI, SF-36, and VAS neck and arm pain scores were noted by the authors as early as 6 weeks postoperatively in the arthroplasty group and shown to be sustained through the 5-year follow-up appointment. The researchers also demonstrated that the Prestige disc effectively maintained more than 6° of cervical segmental motion at 60 months (Fig. 95.4), whereas ACDF restricted segmental range of motion to less than half a degree. Interestingly, despite no statistically significant difference between the investigational and control groups between either subsequent operation for adjacent-segment disease or rate of revision of the index surgery, the patients who underwent arthroplasty reported statistically superior neurologic outcomes.

One recently published study evaluated the combined data from three FDA IDE single-level arthroplasty trials—Prestige ST, Bryan, and ProDisc-C—with at least 2 years of clinical follow-up.¹⁸ Upadhyaya et al. reported rates of fusion for ACDF as better than 95% and noted that both investigational and control groups reported improvement in NDI, SF-36, and VAS pain scores postoperatively. Neurologic success, however, as defined by sustained

improvement in motor, sensory, or muscle stretch reflex examinations, was noted to be statistically superior in the arthroplasty cohort. The authors also validated cadaveric, biomechanical studies by demonstrating preserved segmental range of motion in the arthroplasty group. The authors did not find a statistically significant difference in the rate of adjacent segment disease at the 2-year interval.

While all FDA IDE trial publications to date have evaluated single-level arthroplasty, there is some data beginning to emerge that evaluate outcomes of multilevel arthroplasty. In 2010, Cardoso and Rosner presented data based on the 12-month clinical outcomes assessments that multilevel cervical arthroplasty was both safe and effective in treating cervical radiculopathy and myelopathy.⁴⁵ Similarly, a French group published the results of >50 patients who underwent two-level or more arthroplasty, the vast majority of whom (>94%) reported sustained clinical neurologic improvement to an extent similar to a cohort of nearly 200 patients who underwent single-level arthroplasty.⁴⁶ A third study by Pimenta et al. examined multiple- and single-level arthroplasty outcomes, as part of a prospective, consecutive series of 229 patients treated with PCM for an FDA pilot study.⁴⁷ In this study, the authors found statistically significant improvements in disability for multilevel compared to single-level arthroplasty, with all other outcomes equivalent between the two. However, there is some evidence to suggest that multilevel arthroplasty triggers an increased incidence of heterotopic ossification.^{48,49} Of note, early radiographic evidence of heterotopic ossification does not appear to diminish functional outcomes, at least through mid-term follow-up.^{50,51} The long-term clinical implications, possibly related to an increased incidence of spontaneous and unintended fusion, remain undefined.

Overall, cervical arthroplasty has proven to be a viable alternative to traditional fusion operations in improving clinical symptoms of radiculopathy and in preventing the progression of myelopathy. Recent results also suggest that arthroplasty may be superior to ACDF in the overall success and several other parameters when data from the FDA IDE studies are pooled.^{18,19} Importantly, none of the recently published FDA IDE trial results have reported catastrophic events related to the implantation of an artificial disc. Clinical outcomes data with >48 months of follow-up are available for three of the four artificial prostheses described above, and in all cases the follow-up rate

was <80%. Longer-term follow-up (>10 years) is still not yet available from the US FDA IDE trials.

■ COMPLICATIONS

For cervical arthroplasty, anterior approach-related complications including dysphonia and dysphagia are similar to the rates reported in the ACDF literature. Additional complications associated with the implant itself are important to note. These include the rare incidence of implant migration and subsidence.⁵² There is a case report of incomplete paraplegia following dislocation of an artificial disc device into the spinal canal with resultant spinal cord compression.⁵³

Furthermore, heterotopic ossification (HO) after cervical arthroplasty can limit the mobility of an artificial disc. Tu et al. analyzed a total of 107 levels of Bryan disc arthroplasties placed in 75 patients in Taiwan.⁵⁴ Heterotopic ossification was identified in 60 levels (56.1%) by CT scanning. Furthermore, Wu et al. looked at the difference in HO formation between one- and two-level cervical arthroplasty patients.⁴⁸ Their results revealed a significantly higher rate of HO formation (75% vs. 40.5%) in the two-level arthroplasty group in the Taiwanese population. Another study by Pimenta et al. examined the incidence of HO at an average follow-up of 4.5 years (range 1–6 years) in 158 patients who received the PCM disc at 272 levels.⁵⁵ The authors found an HO rate of 7.7% (20 levels). In 91% of patients who developed HO, immediate postoperative imaging was reviewed and remaining osteophytes were observed where HO eventually formed, suggesting the need for diligent surgical technique in the intraoperative management of osteophytes. No relationship between HO and clinical deterioration was found. The long-term effects of HO, however, do warrant further investigation. Certain ethnic subgroups, such as patients of Asian heritage, may be more prone to HO formation. Early HO can potentially be avoided by administering nonsteroidal anti-inflammatory drugs in the immediate postoperative period.

■ CONCLUSION

Cervical arthroplasty is a safe and effective alternative to standard ACDF in addressing single-level degenerative cervical spondylosis in the setting of a corresponding clinical radiculopathy or mild myelopathy, based on four level I evidence studies. Recent investigations have

shown that multilevel use may be equivalent with single-level treatment. As with all surgical procedures, patient selection in cervical arthroplasty is critical in optimizing postoperative symptomatic relief. The thorough preoperative radiographic evaluation includes a cervical MRI or CT myelogram. Dynamic cervical films are recommended to identify concomitant baseline cervical instability or arthritic facet pathology that may predict a poor surgical outcome following arthroplasty. Recent data evaluating outcome measures up to 5 years after cervical arthroplasty suggest that one-level artificial disc replacement surpasses ACDF in long-term symptomatic relief while at the same time preserving focal anatomic segmental range of motion and possibly reducing the incidence of adjacent segment disease.

KEY POINTS

- Cervical arthroplasty is a safe and effective alternative to ACDF in addressing single-level degenerative cervical spondylosis in the setting of a corresponding clinical radiculopathy or myelopathy.
- Cervical arthroplasty preserves anatomic focal segmental range of motion and may reduce the incidence of adjacent segment disease when compared with ACDF.
- Preoperative MRI or CT myelogram should be used to confirm the etiology of cervical radiculopathy or mild myelopathy. Dynamic cervical films should be used as adjuncts in accurately identifying patients who may be suitable for arthroplasty.
- To optimize surgical outcome, the surgeon must take care to size the artificial disc appropriately and to position the graft in the center of the disc space. Above all, especially in patients with radiculopathy, there is no substitute for delicate, thorough nerve root decompression that extends to the uncovertebral joints bilaterally.
- Compared to single-level arthroplasty, initial studies evaluating surgical outcome in two-level cervical arthroplasty suggest that multilevel artificial disc replacement is effective in reducing radicular symptoms, but may be associated with higher rates of heterotopic ossification.

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- To optimize surgical outcome, the surgeon must take care to size the artificial disc appropriately and to position the graft in the midline with the patient in normal, anatomic cervical lordosis. Above all, especially in patients with radiculopathy, there is no substitute for meticulous nerve root decompression that extends to the uncovertebral joints bilaterally.
- Gwynedd E, Sekhon LH, Sears WR, et al. Complications with cervical arthroplasty. *J Neurosurg Spine*. 2006;4(2):98-105.
- The complication rate associated with cervical arthroplasty is estimated to be 6% per level. Strict adherence to proper surgical technique should minimize graft migration and complications associated with the anterior surgical approach. Heterotopic ossification and spontaneous arthrodesis are rare, but negate the benefits of a motion-sparing procedure when it occurs. Postoperative nonsteroidal anti-inflammatory medications may reduce the incidence of heterotopic ossification and unintended fusion.
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- The authors analyzed the combined results of the three randomized US FDA investigational device exemption trials comparing arthroplasty with anterior cervical discectomy and fusion (ACDF) for single-level cervical disc disease with a 2-year follow-up period. A total of 1,213 patients were randomized into two treatment arms: 621 patients received an artificial cervical disc and 592 were treated with ACDF. The arthroplasty group demonstrated superior results at 24 months in neurological success and also had a lower rate of secondary surgeries. At the 2-year time point, the reoperation rate for adjacent level disease was lower for the arthroplasty group when the combined dataset was analyzed using a fixed effects model.

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- Cervical arthroplasty preserves anatomic focal segmental range of motion and reduces the incidence of adjacent segment disease. At 4–5 years follow-up, single-level cervical arthroplasty surpasses anterior cervical discectomy and fusion in symptomatic relief based on the neck disability index,

SECTION

10

Thoracic Spine

Kazuhiro Chiba



Thoracic Disc Herniation

Yukihiro Matsuyama

Snapshot

- » Symptoms
- » Diagnosis

- » Treatment
- » Surgical Treatment

INTRODUCTION

Degenerative diseases in the thoracic spine include thoracic disc herniation, ossification of the posterior longitudinal ligament (OPLL), and ossification of the ligamentum flavum (OLF) causing thoracic myelopathy. In daily clinical practice, these diseases are less frequently encountered compared to diseases of the cervical or lumbar spine. Thoracic disc herniation may develop in one out of one million persons and often presents nonspecific symptoms such as dorsal pain and band-like trunk pain, in addition to lower-extremity paralysis. These symptoms can lead to confusion with a lumbar spine disease, which makes diagnosis difficult in some cases.

Thoracic OLF develops mainly in the lower thoracic vertebrae due to involvement of dynamic factors of the spine, while thoracic OPLL often develops in mid-level thoracic vertebrae, at the apex of physiological kyphosis. The peak age of onset is 40 years old or more, in middle-aged or elderly persons, and there is no clear gender difference. Conservative treatments for thoracic degenerative diseases are often ineffective and surgical treatment is often required. However, such surgery is technically demanding. Here, we discuss the symptoms, diagnoses and treatments including surgical approaches for thoracic myelopathy in patients with thoracic disc herniation.

SYMPTOMS

Many patients with thoracic disc diseases first visit a hospital for nonspecific back pain, band-like trunk pain

or sensory impairment in the lower extremities. These symptoms may be bilateral or unilateral depending on the side of spinal cord compression. Many patients complain lower-extremity muscle weakness and gait disorder, rather than chest symptoms, and are diagnosed with a lumbar spine disease. These symptoms generally aggravate, but often after repeated improvement and aggravation. However, in rare cases, they may rapidly aggravate after a mild injury such as a fall. Spastic paralysis of the lower extremity may occur after aggravation of trunk symptoms, or paralysis may develop depending on body position in the early morning, even without an injury.

Sensory disturbance at the lesion site and below lower-extremity muscle weakness, spastic gait, deep tendon hyper reflexes, positive Babinski reflex and ankle clonus, bladder and rectal disturbance may also be present. Since the clonus and epi conus are located in the thoracolumbar area, more complicated symptoms may also be observed in the lower thoracic lesions. Lower-extremity deep reflex decreases and atrophy of lower-limb muscle may occur along with a decrease in leg strength in such cases.

DIAGNOSIS

Ossification of ligaments and bony spurs of thoracic vertebrae are often unclear on plain X-ray films because the costal bones are located in the thoracic vertebral area.

Therefore, magnetic resonance imaging (MRI) should be performed when a thoracic lesion is suspected based on neurological symptoms. However, even if MRI shows a thoracic compressive lesion, it cannot be clearly judged whether the lesion is due to a herniation, a bony spur, or ossification of the ligament. In such cases, computed tomographic (CT) examination is required before deciding the surgical indication, since CT enables differential diagnosis of disc herniation and a bony spur. When the lesion is soft disc herniation, a posterior approach enables sufficient removal, while an anterior approach is used for a bony spur. A posterior approach for a bony spur requires cost-transversectomy to remove the costal process and costal base. Thus, establishment of the appropriate operative strategy requires the use of CT.

TREATMENT

Conservative treatment is almost always ineffective for spinal cord paralysis caused by a thoracic degenerative disease, and thus surgical treatment is necessary. The results of surgery for the thoracic spinal cord compression in patients with spondylosis and thoracic OPLL are not favorable, but those for thoracic disc herniation are comparatively good. However, the approach to the spinal cord is often more difficult than that in case of a cervical spinal pathology. This is because of the presence of physiological kyphosis in the thoracic spine, in contrast to cervical and lumbar spine, and thus it is difficult to ensure spinal decompression only through a posterior approach. In an anterior approach, decompression of the spinal cord is technically demanding because of the adhesion of the dura mater and ossified ligament, a narrow visual field after a vertical split of the sternum in the upper thoracic spine and the removal of costal bones in the mid to lower thoracic spine. In the following section, we discuss the details of the anterior and posterior approaches for the treatment of thoracic degenerative diseases.

SURGICAL TREATMENT

Anterior Approach

In most cases, a spine surgeon should be able to perform an anterior approach to the thoracic spine with little support from a thoracic surgeon. The important points in an anterior approach¹ to thoracic disc herniation,

especially for middle to lower thoracic disc herniation, are as follows:

Anesthesia

An anesthesiologist performs one-lung ventilation with as little ventilation of the lung on the surgical side as possible. The use of a double-lumen intratracheal tube is recommended.

Choice of Approach Side

The approach should be performed on the side of the herniation. In a second surgery, the approach should be from the side opposite to that used in the previous surgery. If both sides are available, the left side is preferable because the aorta on the left side can be mobilized more easily than the vein on the right side.

Position of the Patient

A lateral position should be used, with a pillow placed beneath the axilla to prevent axillary nerve paralysis, and with the upper extremity in the upside placed on a cedar plate. In addition, the hip and knee joints on the down-side are held in slight flexion to reduce tension of the iliopsoas muscle. The lower extremity in the upside is held in an extended position or in slightly flexed position, with a pillow placed between the lower extremities. A sponge pad should be placed beneath the fibular head of the lower extremity in the downside to prevent peroneal nerve paralysis (Fig. 96.1).

Choice of Costal Bone to be Removed

The costal bone one or two level cranial from the vertebral body or vertebral disc to be exposed should be removed. Especially, for decompression, the costal bone two levels above should be removed to ensure a better surgical field (Fig. 96.2).

Approach to T5/T6

For the approach to T5/T6, the head of the rib of T6 should be removed. A needle inserted into the vertebral disc is used for level confirmation. Segmental arteries of the upper and lower vertebral body are ligated if necessary (Figs. 96.3A and B).

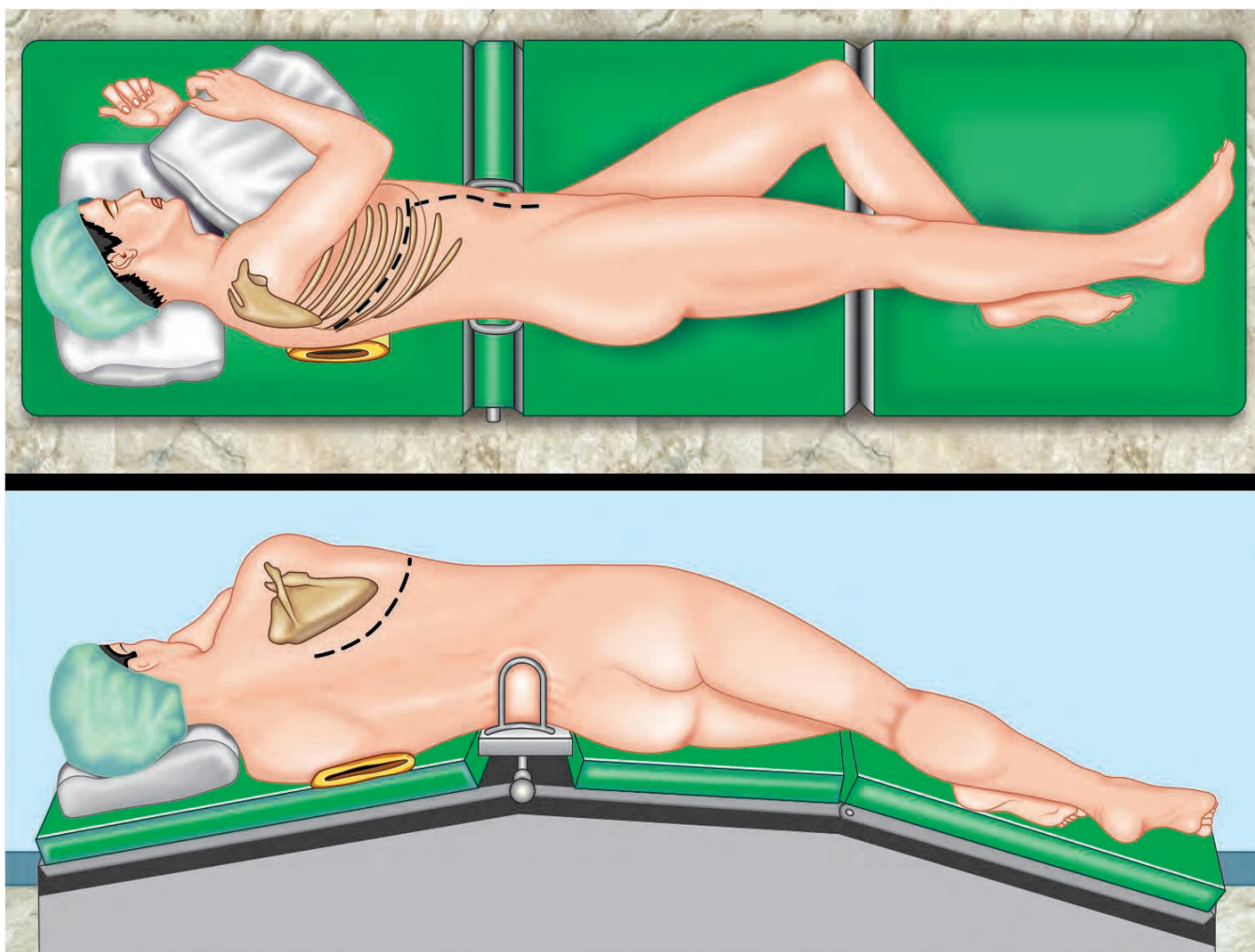


Fig. 96.1: Body position in the approach to middle and lower thoracic vertebrae. The recurvatum position in the lumbar vertebral area makes it easier to perform procedures for the vertebral disc and vertebral body in the thoracic vertebral area.

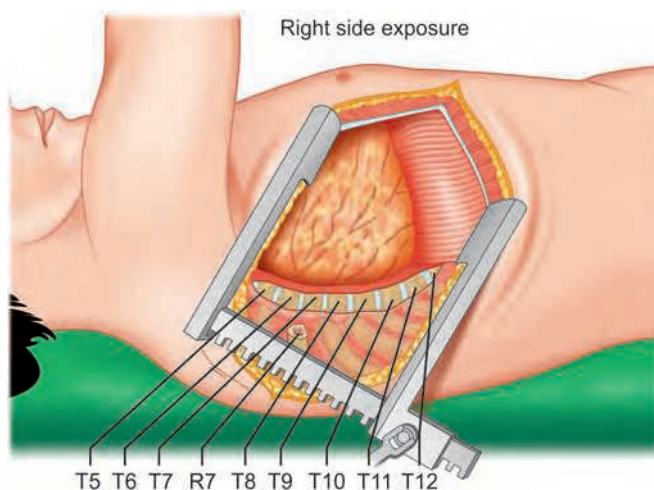
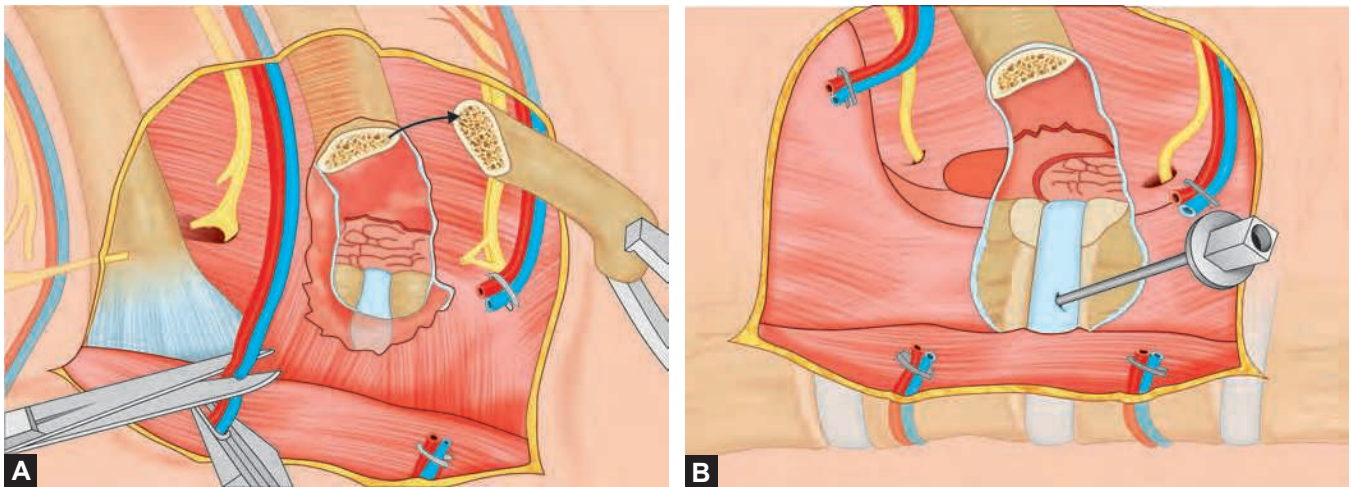
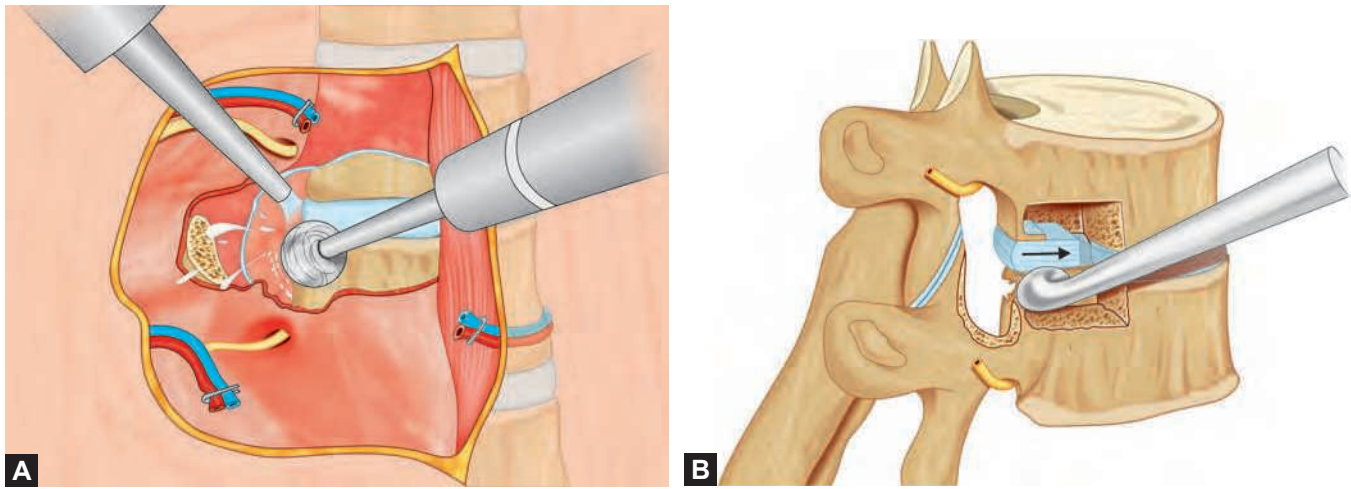


Fig. 96.2: Removal of the No. 7 costal bone. In the approach to middle to lower thoracic vertebrae, removal of the No. 7 costal bone from the rib cartilage to the angle of the rib is preferable. When backward curvature is present and sloping of the costal bone is observed, the No. 5 costal bone should be removed to ensure a good procedure for a curved apical vertebra.



Figs. 96.3A and B: Intervertebral approach. Removal of the head of the rib.



Figs. 96.4A and B: Intervertebral approach. Destruction of the vertebral body and removal of the vertebral disc.

Completion of Spinal Decompression

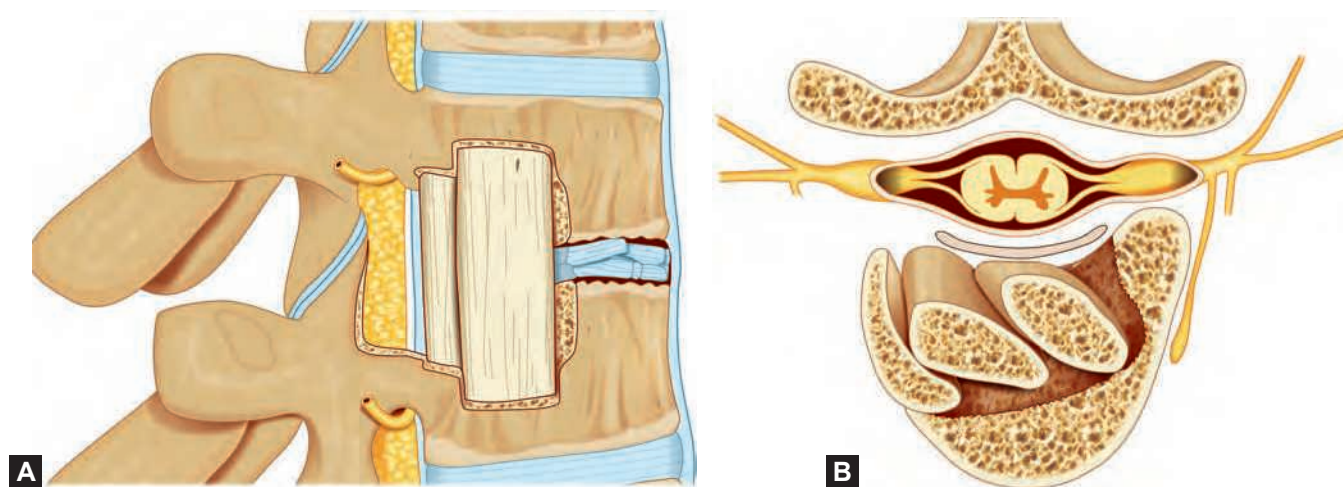
Hemorrhage can be reduced when the vertebral body is dissected and exposed subperiosteally. In the approach for T5/T6, the intervertebral space is confirmed by sliding a raspatorium posterior to the intervertebral disc, and one-third of T5 and T6 vertebrae are excised using an air drill. After thinning of the posterior wall of the vertebral body, the cortex bone is removed using a sharp curette. The vertebral disc is then removed and spinal cord decompression is completed. The important point of this procedure is that the bone in the deep side should be removed first because the dura mater could bulge when the bone in the front side is removed first, after which decompression of the deep part becomes difficult (Figs 96.4A and B).

Bone Graft

After decompression of the spinal cord, the costal bones removed at the beginning of the procedure are trimmed and transplanted (Figs. 96.5A and B).

Posterior Approach

Regarding degenerative disease in the thoracic spine, a conventional laminectomy is insufficient in many cases when a soft disc and a bone spur are to be removed from patients with thoracic disc herniation and spondylosis, respectively. Soft disc herniation may be removed after wide laminectomy or partial removal of the pedicle.



Figs. 96.5A and B: Bone transplantation.

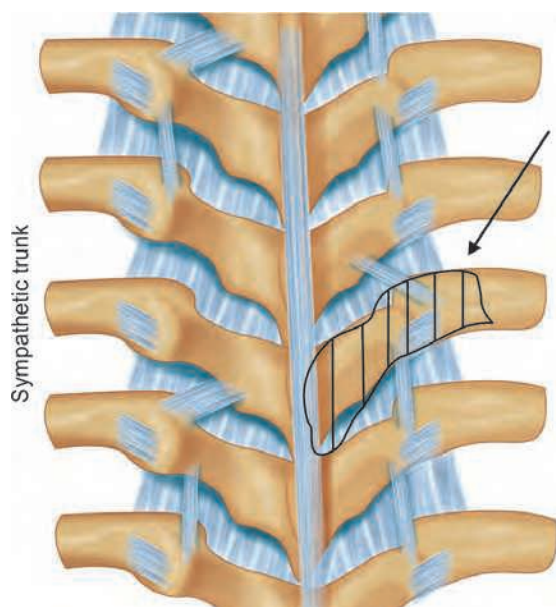


Fig. 96.6: A thoracic vertebra shown from behind, showing the removal range of the costal process and costal bone. Arrow represents bony section to be resected.

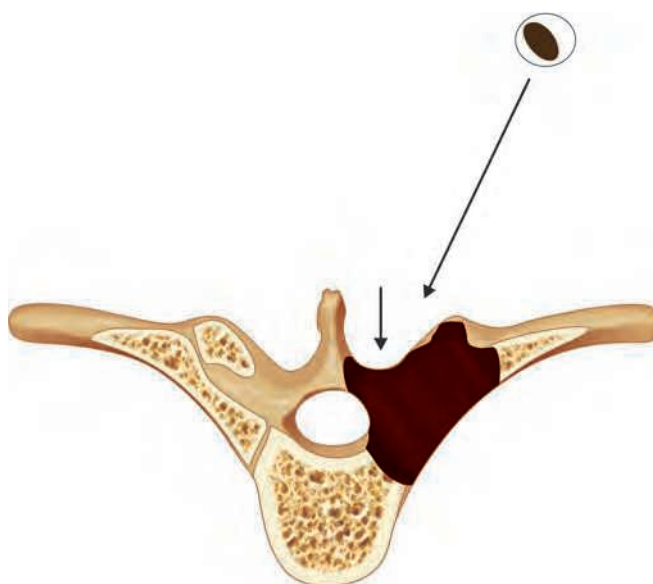


Fig. 96.7: An axial image of a thoracic vertebra, showing the removal range of the costal process and costal bone, in addition to the visible range from the posterolateral side.

However, these procedures are insufficient for the removal of a bone spur, and thus, the removal of the transverse process and the rib head are required. The scheme for this costotransversectomy^{2,3} is shown in Figures 96.6 and 96.7. In this approach, the unilateral thoracic intervertebral joint should be removed completely and fixation should be performed using an instrument after decompression.

Representative Case

In this case, preoperative MRI and myelopathy CT showed that the spinal cord was displaced to the left side by a herniation that ruptured to the right side of the spinal canal at the T5/T6 level (Fig. 96.8). The herniation was removed by a posterior approach, and good decompression of the spinal cord was obtained (Figs. 96.9 and 96.10).

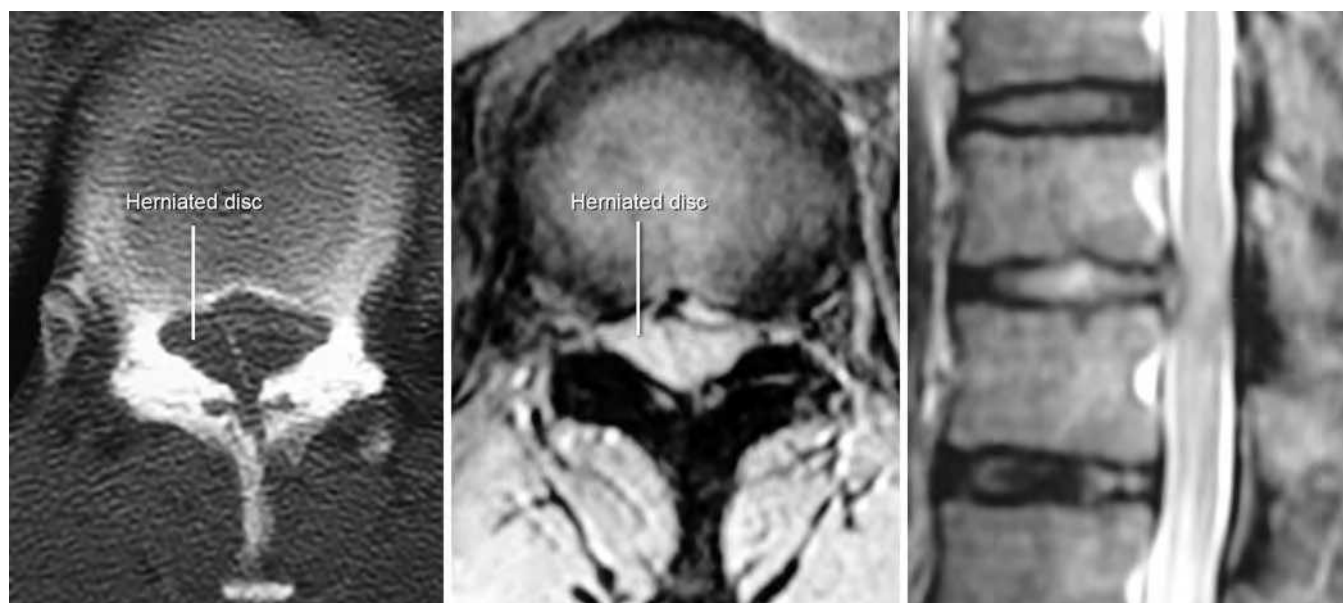


Fig. 96.8: Preoperative T5/T6 herniation in a representative case.

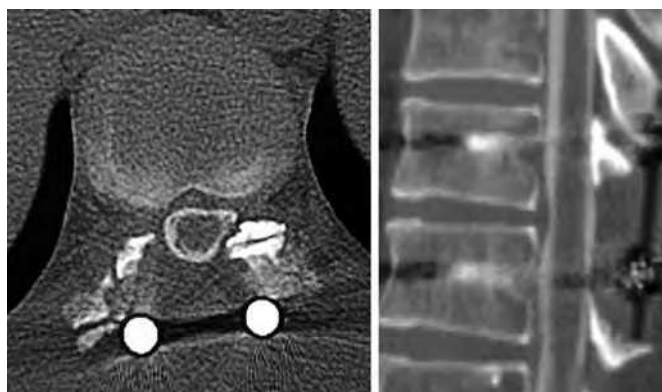


Fig. 96.9: Postoperative myelopathy computed tomography in a representative case.

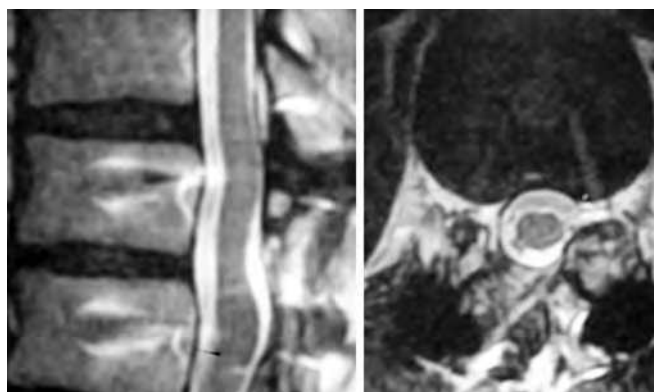


Fig. 96.10: Postoperative magnetic resonance imaging in a representative case.

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Thoracoscopic Approach for Spinal Disorders

Eli M Baron, Daniel Drazin, Neel Anand, J Patrick Johnson

Snapshot

- » Advantages of a Thoracoscopic Approach versus an Open Approach
- » Disadvantages of a Thoracoscopic Approach
- » Patient Selection
- » Preoperative Work-Up
- » Thoracoscopic Technique
- » Outcomes of Thoracoscopic Spine Surgery Procedures
- » Risks of Thoracoscopic Procedures
- » Complication Avoidance

INTRODUCTION

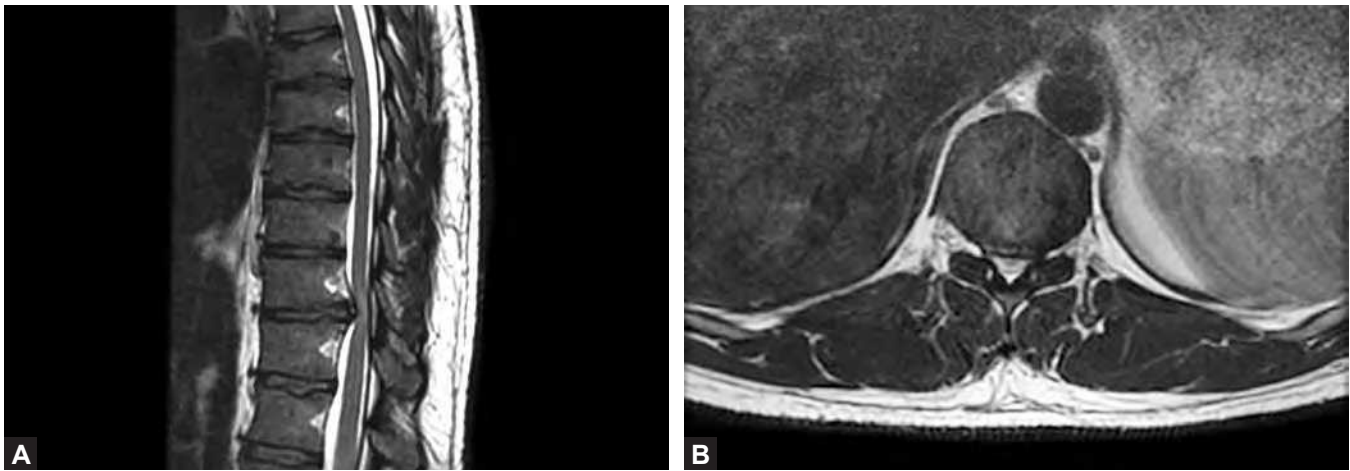
Thoracoscopic surgery is often credited to Jacobeus, where he described in 1910 a thoracoscopic lysis of tuberculosis-related lung adhesion. In actuality, however, Cruise in Dublin was described in an article published in 1879 as performing an endoscopic examination of a chest fistula.¹ Eventually, modern thoracoscopy was developed and its use in the thoracic spine was popularized by Mack et al.² Use of thoracoscopy then expanded to numerous other spinal disorders including but not limited to thoracic discectomy, corpectomy (for trauma, tumor, degenerative change/stenosis, instability, or infection), biopsy, kyphosis surgery (i.e. anterior release for deformity), and scoliosis surgery.³⁻²⁰ Thoracoscopy is also widely used for performing sympathectomies for hyperhidrosis.^{11,21-23} More unusual indications for a thoracoscopic approach to the spine include thoracoscopic approaches for extra-axial tumors (e.g. neurofibromas and schwannomas).^{9,24-26}

ADVANTAGES OF A THORACOSCOPIC APPROACH VERSUS AN OPEN APPROACH

Advantages of using thoracoscopy, as opposed to open thoracotomy, include smaller incision size with less pain

and fewer respiratory complications. Thoracoscopy creates a much smaller wound than open approaches. Adulkasem and Surangsrirat⁶ noted a 4-cm incision typical of thoracoscopy versus 20-cm incisions typical of traditional open approaches. Smaller chest incisions allow for quicker recovery times with shorter hospital stays, less days in the intensive care unit, and subsequently leads to reduced cost.^{6-8,11,13,14} Additionally, forced vital capacity decline may be significantly reduced in the postoperative period, when compared to open surgery.²⁷⁻²⁹ Nevertheless this is controversial, as Lenke et al.³⁰ found no statistical difference in pulmonary function after operation at 2 years in patients undergoing anterior release for adolescent idiopathic scoliosis correction. The use of small portals also avoids the need for rib resection, thus avoiding complications related to disruption of the neurovascular bundle. Small portals also minimize muscle transection, avoiding patient morbidity.³¹

Thoracoscopy has additional theoretical benefits. The video feed from the surgery is readily observed by other surgeons or trainees. Additionally, as the field of remote surgery or robotic-assisted surgery further develops, it may readily be integrated with videoscopic and thoracoscopic technologies. The ability to have a skilled spine surgeon operate on injured people at varied locations would be invaluable.³¹



Figs. 97.1A and B: T2 sagittal and axial magnetic resonance imaging showing a large central thoracic disc herniation.

DISADVANTAGES OF A THORACOSCOPIC APPROACH

Visualization during thoracoscopy may not be as good as that during open approaches where binocular vision and the use of the operating microscope are feasible. Thoracoscopy depends on television projection and many endoscopes only provide two-dimensional vision. Additionally, longer instruments, cleaning of the instrumentation (specifically bone dust from endoscopes) and a different hand eye coordination skill set than is used for open surgery may present difficulties for using this technique.⁴

PATIENT SELECTION

For thoracoscopic discectomy, Johnson et al. recommended patient selection based on the number of levels involved, the complexity of the lesion involved, the presence of ossification of the posterior longitudinal ligament and whether the patient had undergone prior transthoracic surgery. Patients with three or more disc herniations that need to be addressed, those with multisegment ossification of the posterior longitudinal ligament, and those having undergone prior transthoracic surgery may benefit from open thoracotomy over a thoracoscopic approach.⁴

For spinal deformity correction, the ideal patient for thoracoscopic approach has a curve of less than 70° with >50% flexibility or has a single structural thoracic curve or a double or triple curve where only the thoracic curve is structural.³² Liu and Kit³³ noted the optimal surgical candidate for thoracoscopic discectomy/fusion and instrumentation in scoliosis correction to be a right side thoracic,

adolescent idiopathic scoliotic curve of King 3 or Lenke type 1. They recommended that the magnitude of the structural curve should be less than 80°, thoracic kyphosis less than 40° and the weight of patient between 30 and 70 kg. They also suggested that King type 2 and Lenke type 3 and type 5 curves be considered for the procedure. Obesity and intrathoracic pleural adhesions are considered relative contraindications to the procedure.³² Thoracoscopy may also provide a minimally invasive approach to fusionless anterior scoliosis surgery in carefully selected patients with adolescent idiopathic scoliosis.³⁴

PREOPERATIVE WORK-UP

For thoracic disc herniations, magnetic resonance imaging provides useful information regarding spinal cord versus nerve root compression (Figs. 97.1A and B). Computed tomography (CT) provides detailed information regarding bony anatomy and provides more accurate information regarding calcifications in the canal and calcified disc herniations.³⁵ Patients should have preoperative lumbar and thoracic plain X-rays to assist in localization in the operating room.

THORACOSCOPIC TECHNIQUE

For the purposes of this chapter, we refer here to thoracoscopic discectomy.

Positioning and Room Setup

The patient is positioned in the lateral decubitus position, after induction of anesthesia and placement of a double

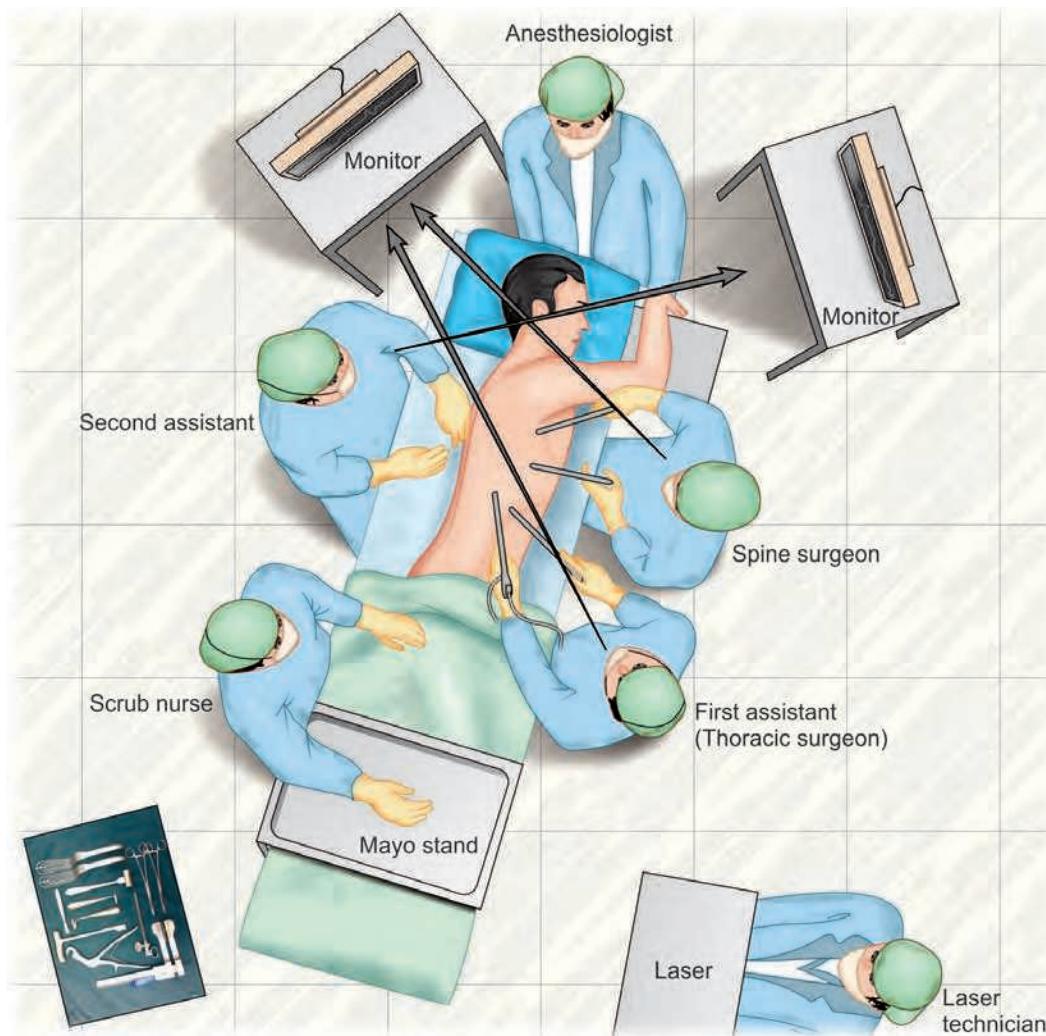


Fig. 97.2: Room setup for thoracoscopic surgery.

lumen endotracheal tube. The ipsilateral lung is collapsed, facilitating performance of the procedure while the contralateral dependent lung is ventilated. Standard neuromonitoring is used.⁴

In the lateral decubitus position, an axillary roll is used. Bony prominences and superficial nerves such as the peroneal nerve are padded and protected.³⁵ An anteroposterior (AP) radiograph is taken with markers placed on the chest wall to help determine portal position. The skin is then marked and the patient is prepped widely for possible need for thoracotomy and/or a posterior approach.^{4,35}

The surgeon and first assistant will typically stand at the abdominal side of the patient with the scrub tech at the foot of the bed. If required, a second assistant can stand at the posterior side of the patient. Video monitors should

be directly and comfortably seen by both the primary surgeon and assistants (Fig. 97.2).³⁵

Technique

Typically three endoscopic port sites are used for thoracoscopic discectomy: one is placed in the posterior axillary line and two are placed along the anterior axillary line (Fig. 97.3). Usually an endoscope is placed into the port along the posterior axillary line and instruments are used in the anterior ports. Retraction of the lung is performed and adhesions are lysed as necessary. The patient bed can be rotated to allow the lung to fall forward.

Localization can be performed by counting from the first rib and then confirmed radiographically. Usually segmental vessels are spared, but they can be retracted,

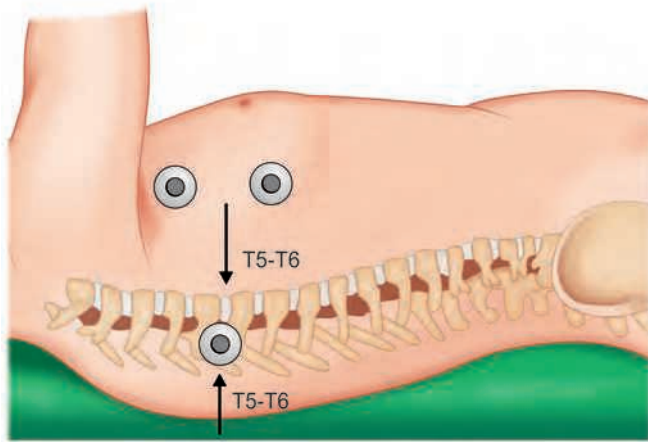


Fig. 97.3: Locations of port sites.

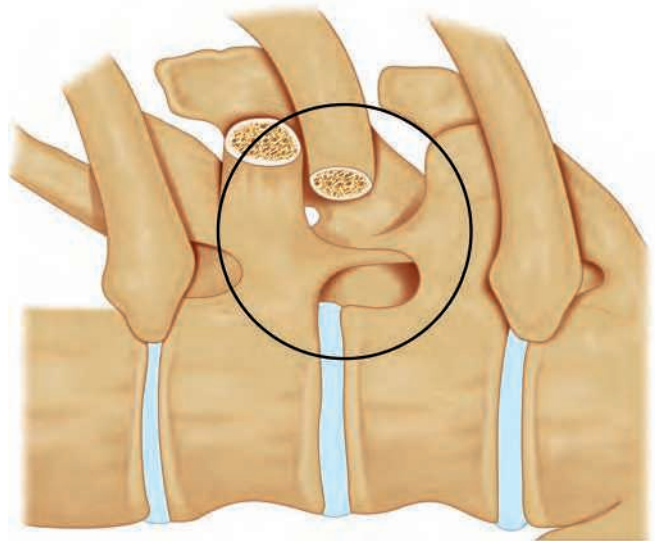


Fig. 97.4: Extent of bone removal.

cauterized and/or divided as necessary. The parietal pleura is dissected of the rib head and adjacent disc space using a harmonic scalpel.

A drill is used to remove the proximal 2 cm of the rib head and the lateral wall of the pedicle and the neuroforamen are exposed (Fig. 97.4). The caudal pedicle is then drilled. The posterior margin of the vertebrae is palpated and the inferior and superior endplates of the vertebrae along the disc space are burred. A trough is drilled within the vertebral body, leaving a ventral shell of bone along the spinal cord to protect the dura and cord. This may need to be deepened all the way across the contralateral pedicle depending on the size and location of pathology. The distance drilled should be verified with AP fluoroscopy. The anterior two thirds of the vertebral body should be left intact to preserve stability. Additionally, the rostrocaudal distance drilled in the vertebrae depends on the size and location of disc herniation.^{4,35} Alternatively, neuronavigation can be used to define the extent of bone removal and help localize a disc herniation.^{7,36,37}

After completion of burring, disc is removed from the disc space. The thinned out cortical floor of the spinal canal is then removed with curettes and Kerrison rongeurs. A probe or nerve hook can be used to then open the posterior longitudinal ligament and disc herniation is pulled into the trough that was previously created. This avoids manipulation of the spinal canal (Figs. 97.5A and B).

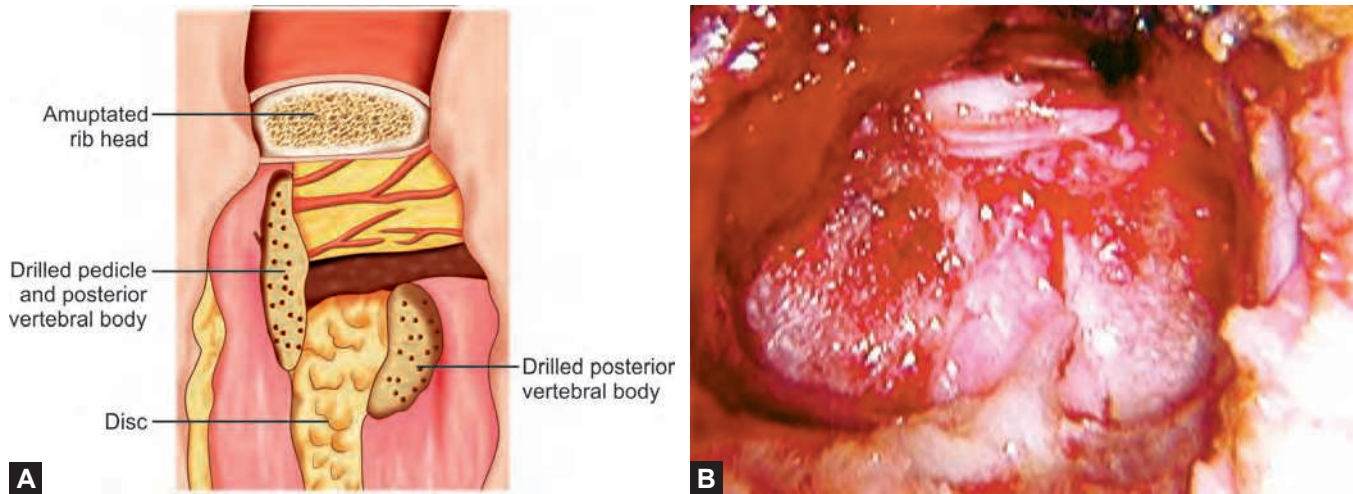
Meticulous hemostasis is then achieved. Bone grafting and fusion can then be performed in certain cases if decompression is extensive. A chest tube is placed through one

of the portals and is guided to the apex of the thoracic cavity. The lung is reinflated and the chest tube is placed to suction at 20 cm. The fascia is closed in a watertight manner and the skin is closed with buried interrupted absorbable sutures.

Typically, patients are ambulated by postoperative day 1 and chest tubes are removed by postoperative day 2 when there is less than 100 mL of drainage.^{4,35}

■ OUTCOMES OF THORACOSCOPIC SPINE SURGERY PROCEDURES

Anand and Reagan reported minimum 2-year follow-up outcomes on 100 patients who underwent video-assisted thoracoscopic discectomy.³ Forty patients underwent fusion, of whom 27 underwent rib graft placement and 13 had thread cages placed. Mean operative time was 173 minutes and mean blood loss was 259 mL. They noted an average stay of <1 day in the intensive care unit and 4 days in the hospital. They noted minor complications to occur in 21 patients, all of which resolved. There were no cases of neurologic worsening. Four patients underwent a secondary fusion, and a pseudarthrosis developed in one patient. At 2 years, 73% patients had an improvement in Oswestry score of 20% or more, which was defined as a clinical success. They concluded, "Video-assisted thoracoscopic surgery appears to be a safe and efficacious method for the treatment of refractory symptomatic thoracic disc herniations."



Figs. 97.5A and B: Decompressed spinal cord after bone, ligament and disc herniation removal.

Johnson et al. compared outcomes of 36 patients undergoing thoracoscopic discectomy with 8 patients who underwent open thoracotomy and discectomy.⁴ Lesions included soft and calcified disc herniations, Ossification of the posterior longitudinal ligament (OPLL), and discitis. They noted operative times, blood loss, and duration of chest tube drainage to be lower in patients who underwent thoracoscopy than in those who underwent open thoracotomy but were not statistically significant. Narcotic usage and hospital stay were significantly less for patients in the thoracoscopy group. Both groups largely improved neurologically. The authors concluded, "Thoracoscopic discectomy procedures have several distinct advantages over conventional procedures primarily related to reduced surgery-related pain, morbidity, length of stay, and complications. The need for adequate training and consistent surgical experience to maintain effective skills is necessary for surgeons performing thoracoscopy."

In their early landmark paper on thoracoscopic spine surgery, Newton et al.²⁹ reported 38 patients on whom endoscopic thoracic spine surgery was performed to correct idiopathic scoliosis. Approximately 5.5 hours were required to fuse an average of seven levels. The average incision length was approximately 10.5 cm. This was estimated to be one third of the length of an incision required for an open procedure. Cosmetic outcome of using this approach should not be overlooked. They used as their controls 68 patients for whom an open procedure had been performed. Deformity correction achieved was comparable to the patients for whom open procedures were performed.

Morbidity was less compared to the open procedure. The length of the surgery was longer for the thoracoscopic group, but this was felt to be a function of the learning curve for thoracoscopy.

Han et al.¹¹ reported their experience with 241 thoracoscopic procedures. These procedures include 164 thoracic sympathectomies, 60 discectomies, 5 neurogenic tumor resections, 8 corpectomies and spinal reconstructions, 2 anterior releases, and 2 biopsies. Ninety-eight percent of patients undergoing discectomies had complete decompression. They concluded this approach to be effective and to be comparable with the open procedures. They further concluded that thoracoscopy provides better visualization of the ventral spine and spinal cord than open approaches and is associated with lower morbidity rates when compared with open surgery. Furthermore, they believed that the procedure was associated with less discomfort and superior cosmesis than the traditional open approach. They also noted that thoracoscopy was faster and associated with less blood loss.

Assaker et al.⁷ reported on two patients for whom their endoscopic spine surgery was supplemented with image guidance. Patient 1 presented with a T8-T9 calcified disc and myelopathy. Patient 2 presented with lumbosacral pathology and will not be discussed further in this section. While Patient 1 did well postoperatively, the disadvantage of significant time for positioning and preparation detracted from the value of the technique. The authors postulate that with a specialized operating suite with a mobile CT scanner, the preparatory time could be significantly reduced.

Rosenthal et al.¹³ reported on their experience with herniated thoracic discs. Fifty-five patients underwent thoracoscopy. Mean surgical time was 3 hours and 25 minutes. Mean blood loss was 327 mL. When comparing thoracoscopy with costotransversectomy, they noted better resection of midline thoracic discs in the former because the thoracoscopy afforded better visualization of the anterior dura. Clinical outcomes were reported as excellent, with 22 of 36 myelopathic patients having excellent recoveries.

Huang et al.³⁸ reported on complications in 90 consecutive patients with various indications for thoracoscopic spinal surgery. The pathologies include 41 spinal metastases, 13 scoliotic patients, 12 burst fractures, 10 cases of Pott's disease, 8 cases of pyogenic spondylitis, 2 thoracic disc herniations, 2 cases of ankylosing spondylitis with diskitis, 1 osteoporotic compression fracture, and 1 case of thoracolumbar kyphosis. Thirty complications in 22 patients were noted (24.4%). Two fatalities were recorded (hemorrhage and postoperative pneumonia). Other complications noted included intercostal neuralgia, wound infection, atelectasis, pneumothorax, pharyngeal pain, subcutaneous emphysema, pericardial penetration, screw malposition, and graft dislodgement. Four patients required conversion to open thoracotomy.

Huntington et al.³⁹ used an ovine model to address the question of the ability of thoracoscopic discectomy versus open thoracic discectomy to adequately decompress the disc space. They used a total of 60 sheep in their study. After surgical intervention, the sheep were euthanized and dissected. Photographs of the vertebral end plates and remaining discs were analyzed with computer imaging. The results revealed no significant difference in the amount of disc resected, further supporting the use of an endoscopic technique.

■ RISKS OF THORACOSCOPIC PROCEDURES

As with many endoscopic approaches, the ability to broadly visualize the working field is limited by the view of the endoscope. Injury to adjacent critical structures may occur and may necessitate conversion to an open procedure.³¹ The surgeons involved may require additional training with steep learning curves. For procedures requiring image-guided navigation, there may be an increased exposure risk from radiation for patients and all operating room personnel.⁷

Cheung and Ghazi⁴⁰ reviewed complications associated with thoracoscopic approaches to the spine. They noted that complications associated with thoracoscopy are similar to those seen in open procedures with variation in the incidence of complications. These can be subclassified as complications related to anesthesia/intubation, positioning, and the use of endoscopy. Anesthetic-related complications typically were related to single lung ventilation resulting from incorrect endotracheal tube placement, wrong tube size and under or over inflation of the bronchial cuff; all these can lead to air leak into the operated lung. Other anesthetic/ventilation-related complications include air embolism and pneumothorax. Lateral decubitus positioning may lead to brachial plexus or peroneal nerve injury. Endoscopic technique may result in a vascular injury or injury to the lung parenchyma.⁴⁰ Neurologic injury may also occur, as it may with any manipulation of the spine. Endoscopic instrumentation may also break inside the chest cavity and tips of the endoscopes used may burn tissues.

Complications seen in some of the series involving thoracoscopic approaches to the spine include intercostal neuralgia, pneumothorax, pulmonary embolism, pulmonary edema, pleural effusion, atelectasis, blood loss of ≥ 2000 mL, chylothorax, implant failure (where a fusion occurred), pneumonia, and ileus.^{3,12,41-43}

■ COMPLICATION AVOIDANCE

Patients considered for thoracoscopy, and thoracotomy, should be screened for pre-existing pulmonary disease. Smokers should be urged to stop smoking preoperatively. If patients with pre-existing pulmonary disease are to be scheduled for surgery, pulmonary medicine consultation should be obtained.

Ample padding should be provided during positioning in order to avoid superficial nerve palsies. We also recommend placement of an axillary roll to minimize the risk of axillary nerve injury.³⁵

In terms of the ventilated lung, positive end expiratory pressure while continuous positive airway pressure on the nonventilated lung can minimize risk of respiratory depression and atelectasis. Improper placement of the endotracheal tube may result in decreased arterial oxygen saturation or failure to collapse the lung on the operated side; after positioning the patient in the lateral decubitus position, the double lumen tube's position should be rechecked with bronchoscopy. If insufflation is used to collapse the lung, pressures should be kept below 10–15 mm Hg to minimize the risk of compression of the mediastinum and cardiac tamponade.⁴⁰

Placement of thoracoscopic ports can result in bleeding and in pulmonary injury. The first port placed is always done blindly: placement should be done as gently as possible while avoiding disruption of the neurovascular bundle that runs beneath the ribs. Subsequent ports should be placed under thoracoscopic visualization. Prior to port placement, adhesions may need to be dissected. This can be done bluntly with the surgeon's gloved finger.⁴⁰

Use of soft thoracoscopic ports has been recommended, as they are associated with a reduced incidence of intercostal neuralgia. Stiff portals, however, may more readily allow introduction of instruments into the chest cavity.³⁵

Careful visualization of instruments introduced into the thoracic cavity must occur at all times. This is particularly true regarding fan retractors, dissectors, drills, and any other instruments used around the spinal cord. Bleeding should be kept to a minimum. Any bleeding edges of bone should be waxed. Additionally, bipolar electrocautery and hemostatic clips can be used. If segmental vessels are going to be ligated, they should be ligated close to their origins to minimize the risk of spinal cord infarction. Monopolar cautery should be avoided, especially around the head of the rib, as this may contribute to intercostal neuralgia.^{4,35,40}

If a durotomy is encountered during discectomy, this can theoretically be repaired with a fine suture or patched with fascia. If a leak cannot be repaired, we recommend cerebrospinal fluid diversion with a lumbar drain and placement of the chest tube to water seal drainage to minimize risk of cerebrospinal fluid-pleural fistula.³⁵

All patients should be mobilized as early postoperatively as possible and also be treated with aggressive pulmonary toilet to help reduce the risk of atelectasis, pneumonia, and deep venous thrombosis, among other complications.

CONCLUSION

Thoracoscopic discectomy is a less invasive means of achieving anterior decompression of the thoracic spinal canal. Variations of the technique have been used for treatments of numerous spinal disorders. Careful patient selection, meticulous technique, knowledge of perioperative care and complications, and frequent practice are required for good outcomes.

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Thoracic Discectomy and Corpectomy

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Snapshot

- » Thoracic Disc Disease
- » Thoracic Discectomy
- » Thoracic Corpectomy
- » Complications

INTRODUCTION

Thoracic discectomy and corpectomy are the two major procedures indicated in the surgical management of thoracic spinal disease. Thoracic disc disease, which is much less common than its lumbar counterpart, is typically treated conservatively. When conservative management fails and symptoms persist, or if myelopathy is present, thoracic discectomy is indicated to decompress the thoracic spinal cord and affected nerve roots. Thoracic corpectomy is reserved for certain thoracic burst fractures, tumors, infections, severe deformity, and spinal instability. This chapter describes thoracic disc disease, thoracic discectomy, and thoracic corpectomy.

THORACIC DISC DISEASE

Epidemiology

The actual prevalence and incidence of thoracic disc herniation is unknown, as the majority is either unrecognized or asymptomatic. Most patients are in their fourth to sixth decades of life and there is a slight male predilection.¹⁻⁴ Symptomatic women tend to present at a later age than men.⁵ A small number of adolescents with Scheuermann's disease present with a progressive neurologic deficit secondary to an acute thoracic disc herniation. Between 33% and 50% of patients report a history of trauma or significant physical exertion prior to the onset of symptoms.^{5,6}

In 1995, Wood et al.⁷ evaluated magnetic resonance imagings (MRIs) of from 90 asymptomatic individuals and found thoracic disc abnormalities in 73%. Of these subjects, 37% had frank disc herniation and 29% showed definite cord deformation. In a later study, 20 patients with 48 asymptomatic thoracic disc herniations previously diagnosed on MRI were re-examined.⁸ No patient became symptomatic during the study period, with a mean follow-up interval of 26 months. They also noted that small herniations either remained unchanged or increased in size, while larger herniations tended to get smaller over time. The authors concluded that asymptomatic thoracic disc herniations exhibit relatively little change in size over time and rarely become symptomatic. Numerous other authors have conducted epidemiologic studies of thoracic disc herniation.^{9,10} Most recently, Niemelainen et al.¹¹ reported that degenerative thoracic MRI changes were less common than previously reported. The authors found anterior disc bulging in 45.2% of asymptomatic patients, ages 35–70, and posterior disc bulging in 9.2% of subjects (Fig. 98.1).

Surgical treatment for thoracic disc herniation is rare and only accounts for between 0.15% and 4% of all disc operations.¹²⁻¹⁸ Historically, treatment of this disorder has been problematic. This is partly related to the infrequency of the disease. Furthermore, indications for surgery are not well established because the natural history of the disorder is not clearly defined. In general, the presence of severe or



Fig. 98.1: Sagittal magnetic resonance imaging of thoracic disc herniation.

progressive myelopathy is regarded as an absolute indication for surgery.¹⁸ The role of surgery as a means to control pain is controversial; it has been reported that radicular pain responds better to surgery than does nonradiating, axial thoracic pain.^{19,20}

Etiology

The majority of authors favor degenerative processes as the major cause of thoracic disc herniation.^{1,12,21} This is supported by the finding of higher incidence of disc herniation in the lumbar spine, where greater degenerative changes are noted. In their cross-sectional study of men 35–70 years of age in the Finnish Twin Cohort, Niemelmainen et al.¹¹ noted moderate-to-severe thoracic disc height narrowing in 21.4% of the subjects.

Although the role of degeneration in the etiology of thoracic disc disease is well accepted, the role of trauma as a cause of herniated thoracic discs remains controversial. A history of trauma can only be elicited in 14–63% of patients with a thoracic disc herniation.^{3,22} The degree of reported trauma responsible for the herniation is also quite variable, ranging from minor twisting mechanisms to major falls or motor vehicle accidents.²³

Finally, Scheuermann's disease has been implicated as a potential causative process for thoracic disc disease. Numerous authors have postulated an association between the primary pathologic process of the disease or secondary degeneration due to the disease resulting in increased incidence of disc herniation.^{24–27}

Clinical Presentation and Diagnosis

The differential diagnosis of thoracic pain is variable and includes both spinal and nonspinal pathologies. Although not exhaustive, Vanichkachorn et al.⁵ presented a comprehensive list of both nonspinal and spinal causes that should be considered in patients presenting with thoracic pain. Nonspinal causes can include intrathoracic (cardiovascular, pulmonary, and mediastinal), intra-abdominal (hepatobiliary, gastrointestinal, retroperitoneal), and musculoskeletal (post-thoracotomy syndrome, polymyalgia rheumatic, fibromyalgia, rib fractures) pathologies. Spinal causes include infectious, neoplastic, degenerative, metabolic (osteoporosis, osteomalacia), deformity (kyphosis, scoliosis, trauma), and neurogenic etiologies.

Although there is extreme variation in the clinical presentation of patients who have a herniated thoracic disc, they can generally be divided into three groups depending on the symptoms at presentation: predominantly axial pain, radicular pain, or thoracic myelopathy.⁵ Arce et al.¹² characterized the patterns of typical initial presentation for thoracic disc herniation: 57% described pain, 24% described sensory disturbance, 17% described motor weakness, and 2% described bladder dysfunction.

Pain, whether axial or radicular, is the most common presenting complaint for patients with a symptomatic thoracic disc herniation. Axial pain is usually localized to the middle to lower thoracic region; however, in some circumstances, it may have a radiating component referred to the middle to lower lumbar spine. The pain is generally characterized as mild to moderate in intensity.⁵

Thoracic radiculopathy is often described as pain in a band-like distribution following a discrete dermatome. The T10 dermatomal level is the most commonly reported distribution regardless of the involved level. Radicular pain is typically accompanied by axial pain. Sensory changes including paresthesia and dysesthesia are the second most commonly reported symptoms of acute thoracic disc herniation.

The most urgent and worrisome presentation of thoracic disc herniation is myelopathy. Weakness and upper motor neuron signs including clonus, gait disturbances, and spasticity can indicate thoracic cord compression. Concurrent cervical disease should also be suspected and investigated in these patients. However, patients with thoracic myelopathy without cervical myelopathy may present with upper motor neuron signs in the lower extremity, without upper extremity complaints.

In addition to a thorough physical examination to confirm a spinal etiology, a clinician must evaluate the entire spine to differentiate between the cervical, thoracic, and lumbar spine as a source of the patient's symptoms. Advanced imaging modalities are critical to confirm suspected diagnoses from the clinical exam, and include plain radiographs (including flexion and extension views), computed tomography (including myelography when indicated), and MRI.

Nonoperative Management

Because the vast majority of patients present with pain without myelopathy, the natural history of most acute thoracic disc herniation is benign and mimics the course of herniation in the lumbar spine. The management of acute thoracic disc herniation is, therefore, similar to nonoperative management protocols for patients with acute lumbar herniation.⁵

In the acute phase, activity modifications, anti-inflammatory drugs, and physical therapy are the conservative modalities of choice. Brown et al.²⁸ reported successful nonoperative treatment of 63% of patients with a symptomatic disc herniation. Additional nonoperative interventions include intercostal nerve injections and, occasionally, bracing, although little literature exists proving the efficacy of these treatments.

THORACIC DISCECTOMY

Indications and Contraindications

Surgical treatment for thoracic disc herniation is rare and only accounts for between 0.15% and 4% of all disc operations.¹²⁻¹⁸ Thoracic discectomy is indicated for the minority of patients. In patients with an acute disc herniation with myelopathic findings attributable to the lesion, especially if there is progressive neurologic deterioration, discectomy may be indicated. In addition, selected patients with persistent and intolerable pain who have failed conservative measures may be considered for thoracic discectomy.

Surgical Approach

Selection of the optimal surgical approach for discectomy is controversial. Historically, patients treated with laminectomy alone resulted in suboptimal outcomes, likely related to the ventral force placed on the spinal cord by the herniated disc that is inadequately reduced by removing

only the lamina.^{17,18,20,29,30} When discectomy was performed via laminectomy, spinal cord manipulation was often not well tolerated, due to the limited space available for the spinal cord in the thoracic spine and its tenuous blood supply.^{14,28-31}

Surgical approaches that avoid these issues can be grouped into anterior approaches, including transthoracic; posterior approaches including laminectomy and pediculofacetectomy; and lateral approaches, including costotransversectomy and lateral extracavitary exposure. The actual approaches are discussed in a previous chapter, as are their advantages and disadvantages, which must be carefully considered when selecting the method of exposure.⁵ In this section, we will focus on the actual discectomy accomplished once the surgical approach is complete.

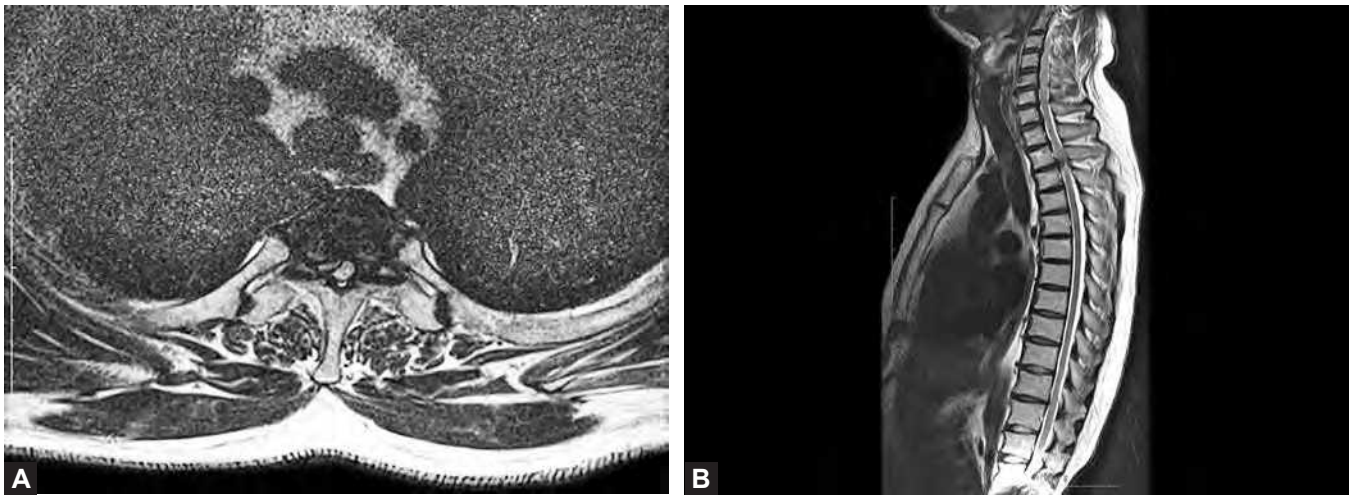
Anterior Approaches

The transthoracic approach is the most commonly used anterior approach to the thoracic spine. Advantages to this approach include a more direct approach to the disc and better visualization, facilitating excision of a central herniation and a herniation with intradural penetration. Few complications have been described after thoracotomy for discectomy.^{12,22,32-36}

The patient is placed in the lateral decubitus position. In general, lateral prolapse is best approached from the ipsilateral side; a midline herniation may be approached from either side. The right side has the advantage of avoiding the great vessels and the heart in the upper and middle thoracic spine, and a statistically lower risk to the artery of Adamkiewicz because it is located on the left in approximately 80% of patients.^{37,38} After the approach is complete, the recommended extent of bone and disc removal varies from a small amount in the posterior aspect of the disc to complete discectomy with partial corpectomy of the adjacent bodies.^{22,32,34,35} Partial corpectomy provides the greatest degree of visualization and allows for more complete discectomy (Figs. 98.2A and B).

Posterior Approaches

The posterior approach to the thoracic spine is the workhorse approach for many spinal conditions. However, as detailed earlier in the chapter, decompressive laminectomy from a midline approach for thoracic discectomy is largely historical. Frequent morbidity associated with posterior laminectomy for thoracic discectomy—including neural



Figs. 98.2A and B: Schematic photographs demonstrating the transthoracic approach to the thoracic spine.

injury, inadequate decompression, and continued symptoms—has led to the abandonment of this technique.⁵ Arce et al.⁴ reviewed 135 patients after laminectomy for thoracic discectomy, and found that only 58% improved, 10% were unchanged, 28% were made worse, and 4% died.

As a result, more specifically for thoracic disc disease, decompressive laminectomy and thoracic discectomy through a posterior transpedicular, posterolateral extracavitary, or costotransversectomy approach may avoid many of these complications. However, it should be noted that these approaches are frequently destabilizing and typically performed along with a spinal fusion and stabilization with instrumentation.

Transpedicular Approach

The transpedicular approach in thoracic decompression was first described in 1978 and is used mainly to decompress associated nerve roots in soft disc herniations.^{39–42} The details of this surgical approach are discussed in a previous chapter. This technique is best suited for the removal of lateral and some soft paramedian disc herniations in the upper thoracic spine and is aided by the use of the operating microscope.

The appropriate level is determined and the thoracic pedicle overlying the disc herniation is identified. The superior and inferior facets are often removed to allow better exposure of the intended pedicle. The central portion of the pedicle is then removed with a high-speed bur. The medial and superior cortical bone is removed, maintaining the lateral and inferior portions of the pedicle.

Disc material is then removed through this opening, taking care not to injure the cord or nerve roots during this process. Performing a laminectomy before this stage allows for clear identification of the exiting nerve root. Le Roux et al.¹⁹ reported on 20 patients with thoracic disc herniation treated through a transpedicular approach. At the 1-year follow-up, 100% had significant improvement and 40% had no reportable symptoms. Levi et al.⁴³ reported similar good results with the approach. Concerns of instability caused by this approach led to the development of a transfacet pedicle-sparing approach.¹⁷

Posterolateral Approaches

The two most commonly used posterolateral surgical exposures for thoracic discectomy are the lateral extracavitary and costotransversectomy approaches. The lateral extracavitary approach is a modification of the lateral thoracotomy approach described by Larson for use in treating spine disorders.^{5,44} Again, the details of the approach are discussed in a prior chapter. Once the surgeon has resected the rib and the transverse process is removed, the neurovascular bundle can be followed to the neuroforamen. The pedicle is taken down. After the transverse process and pedicle have been removed, discectomy can be performed. If additional exposure is needed to obtain additional discectomy, the vertebral body can be decompressed, making sure to leave a rim of cortical bone just ventral to the thecal sac to protect the spinal cord.

Costotransversectomy, first used in 1900 by Menard for the drainage of a thoracic tubercular abscess, can be

performed in either a prone position or with a classic posterolateral approach. Details of the approach can be found in a prior chapter. This approach does not violate the pleura and is very useful in the removal of paramedian and lateral disc herniations in the entire thoracic spine.⁵ It is not generally the desirable approach when a complete anterior decompression is needed in a case of advanced myelopathy.

Minimally Invasive Techniques

As technology has progressed, spine surgeons have used smaller incisions and found minimally invasive techniques for simple discectomy or decompression of individual nerve roots. Thoracoscopy has the potential advantage of avoiding the pulmonary complications and morbidities of an open thoracotomy. Regan et al. first reported the use of thoracoscopy for the treatment of spinal disease, using the technique to biopsy and drain a thoracic paravertebral abscess.⁴⁵ In the past 5 years, numerous minimally invasive techniques have been described for thoracic discectomy, including advances in thoracoscopy, use of endoscopy, and tube-assisted approaches among others.^{35,42,46-60}

THORACIC CORPECTOMY

Indications

The indications for thoracic corpectomy include burst fractures, tumors, infections, severe deformity, and spinal instability.

Infection

The actual mechanism for spinal infections remains controversial; evidence exists to support both arterial and venous hematogenous spread, local extension from nearby infections, and direct inoculation. Authors who support an arterial mechanism of spread note that the region near the anterior longitudinal ligament is an area where infections typically begin, which has an arteriole network that is susceptible to bacterial seeding.⁶¹ Advocates of venous hematogenous spread argue that organisms are carried to the spine via the plexus of Batson, similar to tumor metastases.⁶²

Trauma

Unlike the cervical and lumbar spine, the thoracic spine is stabilized by the vertebral column, and receives additional

stability from the surrounding ribs and sternum. Anatomically, this has been described as the “fourth column” and Shen and colleagues have shown it to be a clinically significant entity. As a result, typically the thoracic spine requires high-energy injury to produce instability or significant fracture. Although most injuries do not involve significant neurologic deficit, when deficit does occur, complete deficits are more common in the thoracic spine due to the small neural canal and tenuous blood supply.^{63,64} If operative treatment is required, typically, decompression involves corpectomy to provide adequate exposure and decompression of the spinal cord.

Tumor

Metastatic disease to the spine has become increasingly prevalent with better treatment and longer patient survival. It is estimated that between 5% and 33% of all patients with systemic malignancy will have spinal involvement.⁶⁵⁻⁶⁷ Over 90% of spinal tumors are metastatic lesions with a distant primary source. Primary sources include the breast, prostate, lung, kidney, and thyroid.⁶⁸ The primary concerns when treating spinal metastases are: preservation of neural function, maintenance of mechanical stability, and minimization of overall morbidity. Treatment should be designed to maximize meaningful survival outside of the acute care setting.⁶⁹

Operative Treatment

Thoracic corpectomy can be accomplished through an anterior approach, costotransversectomy, thoracic transpedicular approach, or a variety of newer minimally invasive approaches. Although these approaches are discussed in detail in previous chapters, it is worthwhile to note here that, in the thoracic spine, although the T1 nerve root should be preserved whenever possible, in some cases, it may be necessary to perform a rhizotomy of the one of more of the remaining thoracic roots.

Corpectomy

Once the vertebral body is identified in the surgical approach, discectomy is performed both above and below the level of corpectomy. This is accomplished by incising the annulus, elevating the disc to separate it from the endplates, and then completing the discectomy using curettes and rongeurs. The corpectomy is started using a burr and completed by removing the remaining bone with a rongeur. Depending



Figs. 98.3A to C: Sagittal plain X-ray (A), computed tomography scan (B), and magnetic resonance imaging (C) of an 85-year-old woman with 5 weeks of mid-thoracic back pain after a ground-level fall. The patient sustained T6–T8 compression fractures with a significant kyphotic deformity.



Figs. 98.4A and B: The patient described in figure 98.2 was initially managed conservatively; however, she began to develop neurologic deterioration with myelopathy. She underwent T7 and T8 corpectomies with interbody cage placement and instrumented fusion from T4 to T11. She had remarkable improvement in neurologic function postoperatively.

on the pathology, the posterior longitudinal ligament (PLL) may need to be removed for the purposes of decompression. For traumatically retropulsed fracture fragments, care is taken to peel the fragments away from the dura. Once the corpectomy is completed, plating or screw/rod constructs

can be used to stabilize the segment through the same approach. Either bone grafting and cage or allograft is used in place of the removed vertebral segment (Figs. 98.3 and 98.4).

Special Considerations

It is generally considered safe to place an allograft, bone graft and cage, or instrumentation in the setting of anterior spinal infection if a thorough debridement is performed and appropriate postoperative antibiotics are given.^{70,71} Anterior column reconstruction with polymethylmethacrylate is generally reserved for tumor reconstructions in patients with a life expectancy of <1 year, or in patients in whom radiation or chemotherapy is planned.

COMPLICATIONS

Fessler et al.⁷² reviewed the rates of morbidity and mortality as well as complications related to thoracic discectomy, and found similar rates between various surgical approaches if laminectomy was excluded. The surgery-related complications of paralysis and significant paresis have become relatively rare since laminectomy was abandoned, with only five recent cases of postoperative neurologic deterioration reported.^{6,22,73} Continued symptoms after thoracic discectomy are a concern, and has been

reported by several authors.⁷⁴ Bohlman et al.²² reported one misidentified disc level in their series.

Symptomatic spinal instability is another concern following thoracic discectomy and, although uncommon, has been noted by several authors postoperatively.^{18,75} The incidence of cerebrospinal fluid leakage has been reported from 0% to 15% in a published series.⁷⁴ Lung-related complications, including atelectasis, pneumonia, and pulmonary embolism have been reported, but are not associated with any particular approach.^{18,30,70,75-77} Pleural tears are not a true complication, as all transthoracic discectomies involve pleural disruption. During extracavitary approaches, unintentional pleural tears have been reported.³⁰ Infection rates from 0% to 18% have been reported.^{18,30,31,77} Rare complications including postoperative cerebrovascular accidents, incisional hernia, lateral femoral cutaneous nerve injury, and transient paraplegia have all been reported, but are not commonly associated with these procedures.^{6,72,76}

KEY POINTS⁵

- Thoracic disc disease is not nearly as common as lumbar disc disease, but affects persons more commonly in their fourth to sixth decades
- Although the typical management of thoracic disc disease is conservative, thoracic discectomy is an option when nonoperative interventions fail
- Thoracic discectomy is preferable to laminectomy alone, and can be accomplished through anterior, lateral, or posterior approaches with reasonable success, depending on the location within the thoracic spine and the location of the disc herniation
- Thoracic corpectomy is indicated for certain burst fractures, tumors, infections, severe deformity, and spinal instability
- Complications of thoracic discectomy and corpectomy are infrequent since the abandonment of laminectomy, and include infection, lung complications, and persistent symptoms.

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Thoracic Pedicle Screw Fixation

Ivan Cheng, Michael P Stauff

Snapshot

- » Background
- » Anatomy

- » Clinical Utility

BACKGROUND

History

In modern spine surgery, surgeons regularly utilize thoracic pedicle screws in order to achieve segmental fixation in the surgical treatment of conditions such as deformity, tumor, trauma, infection, and degeneration. The use of instrumentation in the thoracic spine began with Harrington distraction rods in the 1960s and advanced to Luque wires and Cotrel–Dubousset hooks and screws in order to achieve segmental control of the thoracic spine.¹ Introduced by Boucher² and popularized by Roy–Camille et al.,³ lumbar pedicle screws were being used regularly by the 1980s. Around this time, spine surgeons were expanding the use of pedicle screws to the thoracic spine; however, many were careful to note the technical difficulty and risks associated with placing pedicle screws in the thoracic spine^{4,5} compared to the lumbar spine. With the advent of more modern techniques, spine surgeons began using thoracic pedicle screws on a more regular basis.^{6,7} Today, thoracic pedicle screws have become the gold standard for segmental fixation of the thoracic spine.

Advantages

There are several advantages to the use of pedicle screws versus hooks or sublaminar wires for thoracic spine fixation. Thoracic pedicle screws allow for three-column fixation and hence allow for greater control of the thoracic

spinal segment. In a biomechanical analysis, Hackenberg et al.⁸ demonstrated greater fixation strength in pedicle screws versus supra-laminar/pedicle hooks in a thoracic cadaveric model. While some studies have demonstrated no significant differences in curve correction,⁹ many studies have demonstrated that the improved fixation strength associated with thoracic pedicle screws allows for greater correction and improved maintenance of correction in deformity surgery. Kim et al.¹⁰ performed a matched, retrospective cohort examination of pedicle screw versus hook constructs for patients with adolescent idiopathic scoliosis at a large deformity center. They demonstrated significantly improved major and minor curve correction, better maintenance of correction at 2 years, improved pulmonary function, and saved an average of 0.8 levels at the distal end of the construct in the pedicle screw cohort.¹⁰ The same group performed a similar analysis comparing pedicle screw and hybrid constructs. Again, they demonstrated significantly improved major and minor curve correction, maintenance of correction at 2 years, and improved pulmonary function in the pedicle screw cohorts.¹¹ Other investigators have also shown similar results in adult deformity patients.^{12–14} Rose et al.¹³ performed a matched, retrospective cohort analysis of adult idiopathic scoliosis patients and demonstrated better curve correction and maintenance of thoracic kyphosis in the pedicle screw cohort compared to the hook/hybrid cohort. Yilmaz et al.¹⁴ compared hook, hybrid, and pedicle screw constructs in a retrospective analysis and showed significantly

better curve correction in the patients treated with pedicle screws. Pedicle screws have also proven to provide greater curve correction for more severe curves greater than 80°. ¹²

The greater biomechanical fixation offered by thoracic pedicle screws has allowed for improved curve correction without disrupting the rib cage through open anterior thoracic approaches. Koptan et al. ¹⁵ showed similar kyphosis correction in Scheuermann's kyphosis patients who underwent all-posterior pedicle screw constructs versus staged anterior/posterior procedures. In another study, Rose et al. ¹³ found that patients with all pedicle screw constructs required less anterior release in order to achieve curve correction in adult idiopathic scoliosis patients. Other investigators have demonstrated superiority of all pedicle screw versus anterior dual-rod constructs for Lenke 5C curves, ¹⁶ and similar results between anterior/posterior approaches and pedicle screw/posterior-only approaches in severe Lenke 1 and 2 curves. ¹⁷ Achieving deformity correction without disrupting the chest cage is important because it has been shown to negatively impact postoperative pulmonary function in adolescent idiopathic scoliosis patients. ¹⁸

Historically, axial derotation in order to correct thoracic prominence in deformity surgery has been difficult to achieve using hook/sublaminar wire constructs. ^{19,20} This difficulty has been mitigated to a certain extent with the fixation strength afforded by thoracic pedicle screws. A recent biomechanical study demonstrated that the rotational control on the thoracic spine increases linearly with each additional linked pedicle screw. ²¹ The rotational control provided by thoracic pedicle screws has been instrumental in the development of direct vertebral rotation and rod de-rotation techniques for reducing the thoracic prominence/rib hump deformity. ^{22,23}

Disadvantages

The drawbacks associated with the use of thoracic pedicle screws include: steep learning curve, proximal junctional kyphosis (PJK), possible increase in operating time, neurologic complications, vascular complications, and cost. Several studies have examined the learning curve associated with placing pedicle screws. ²⁴⁻²⁸ One of the largest studies analyzed 96 consecutive patients with Lenke 1 curves who were treated with thoracic pedicle screw constructs. With an increase in case number over the course of the study, the authors noted decreased blood loss, decreased time per screw, increased implant density, and decreased total

operative time. ²⁵ The steep learning curve associated with the use of thoracic pedicle screws has also been illustrated in other studies looking at residents of different levels ²⁴ and senior surgeons. ^{26,27} In a more recent study, Gang et al. ²⁸ investigated the learning curve of apprentice surgeons using a retrospective cohort analysis. They showed that apprentice surgeons were ready to independently insert thoracic pedicle screws after placing 60 thoracic pedicle screws under the supervision of the chief surgeon. This data clearly demonstrates a steep learning curve for placing thoracic pedicle screws, especially in deformity surgery.

It is clear that thoracic pedicle screws have increased fixation of the thoracic spinal segment; however, it is not clear if this greater fixation leads to a higher risk of PJK. Some investigators have noted a greater decrease in thoracic kyphosis with increasing pedicle screw density ²⁵ or with all posterior pedicle screw constructs versus all anterior dual rod fixation. ²⁹ Many have postulated that this decrease in thoracic kyphosis predisposes to PJK. This may be especially worrisome in adult scoliosis patients who may have osteopenia and other risk factors that could lead to catastrophic failure at the proximal end of the construct. ³⁰ Kim et al. ³¹ examined the incidence and risk factors of PJK in adolescent idiopathic scoliosis patients treated with three different posterior constructs. There was a significantly higher incidence of PJK in the patients treated with all pedicle screws versus hooks, but no significant difference between the hybrid and pedicle screw cohorts. The authors also noted the following risk factors for PJK postoperatively: larger preoperative thoracic kyphosis, greater decrease in thoracic kyphosis postoperatively, thoracoplasty, and male gender. ³¹

Other disadvantages of thoracic pedicle screws are increased operative time, cost, and neurologic/vascular complications. Some purport that placement of thoracic pedicle screws increases overall operative time because of the technical difficulty associated with screw placement. Although more operative time for lengthy procedures is an important consideration, most studies demonstrating an increased operative time were performed during early experience and were not compared to nonpedicle screw cohorts. ²⁵ Other studies directly comparing different instrumentation with pedicle screws have shown no significant difference in total operative time. ^{10,11} It should be noted, however, that these studies were performed at large deformity centers where thoracic pedicle screws were used on a regular basis. The effect of pedicle screw instrumentation on operative time is invariably linked to the learning curve associated with their placement.

The implant costs associated with pedicle screws is higher than older implants, such as hooks or wires.^{9,10} Most studies have demonstrated greater curve correction using pedicle screw constructs, but the postoperative subjective outcomes in deformity patients have not proven to be significantly different.^{10-12,14} Moreover, similar results have been observed when comparing a higher versus lower number of pedicle screws in adolescent idiopathic scoliosis.³² More research must elucidate the most efficacious, yet cost-effective use of instrumentation. This is vital given the findings of a recent study that demonstrated instrumentation to be 29% of the overall costs associated with scoliosis surgery, estimated to be US\$ 29,955–\$60,754 depending on the curve type.³³

Radiation exposure to the surgeon and operating room staff is also a disadvantage in the use of thoracic pedicle screws. The extent of radiation exposure is dependent on the technique used for screw placement. One study outfitted the surgeon with a thermoluminescent dosimeter to estimate radiation exposure to his whole body and thyroid gland during fluoroscopically guided pedicle screw placement.³⁴ This study suggested that the radiation exposure recorded in this study would lead to the upper limit of recommended lifetime radiation exposure after 10 years. Efforts to decrease this exposure would be beneficial for both the surgeon and the operating room (OR) staff. Other disadvantages related to thoracic pedicle screws include the neurologic and vascular complications ranging from minor nerve root irritation to spinal cord or the great vessel injury. These complications are discussed later in this chapter.

There are advantages and disadvantages associated with the use of pedicle screws in thoracic spine surgery. They are not only used most commonly in deformity surgery, but also can be useful for surgical treatment of degenerative conditions, trauma, tumor, and infection. With careful use, thoracic pedicle screws can allow for excellent fixation, but spine surgeons should be aware of the learning curve and technical issues related to placing pedicle screws in order to minimize complications and maximize outcomes.

ANATOMY

Techniques of Thoracic Pedicle Screw Placement

Surgeons utilize multiple different techniques for placement of thoracic pedicle screws. Originally, the freehand techniques for placing lumbar pedicle screws described by

Roy-Camille et al.³ were extrapolated to the thoracic spine and used extensively by surgeons.⁴ Over time, others have refined these techniques using greater knowledge of the detailed anatomy of the thoracic spine.

Today, the most popular freehand technique was described and popularized by Kim et al.³⁵ After subperiosteal exposure of the posterior thoracic spine out to the tips of the transverse processes, the inferior 3–5 mm of the inferior articular facets are removed using an osteotome. The starting point is then identified according to the level (Figs. 99.1 and 99.2; Kim et al. 2004). We should emphasize that the starting points and trajectories described here are specific to the straightforward thoracic pedicle screw insertion technique. The distal-most thoracic starting point at T12 is the junction of the bisected transverse process and lamina, just medial to the lateral edge of the pars interarticularis. Moving to more proximal levels, the starting point moves cephalad and medial until it reaches the most medial starting points at T7–9, which are at the junction of the superior edge of the transverse process and just lateral to the midpoint at the base of the superior articular process. More proximal to T7, the starting point becomes more lateral and caudad. At T1, the starting point is located at the junction of the bisected transverse process and lamina at the lateral border of the pars interarticularis. No thoracic pedicle screw starting point is medial to the midpoint of the superior articular process (superior articular process rule). Following the starting point identification, a burr is used to start the pedicle path to a depth of 5 mm. The 2-mm thoracic pedicle gearshift is pointed laterally and advanced into the pedicle with firm pressure to 20 mm—the typical length of the pedicle isthmus. Then, the gearshift is removed, turned 180°, and advanced into the vertebral body. Any sudden advance of the gearshift should be investigated with a ball-tipped pedicle sound. In the case of a successful thoracic gearshift pass, the surgeon should confirm the presence of a floor and four walls within the pedicle. The pedicle is then typically tapped 0.5–1.0 mm less than the diameter of the intended screw. Following placement of the screw, the surgeon can then confirm intraosseous screw placement by using fluoroscopy and/or triggered electromyography, depending on surgeon preference.³⁵

Alternatives to the freehand technique generally involve either fluoroscopy or computed-tomography (CT) navigation. Fluoroscopy-guided techniques use multiplanar imaging in order to determine the starting point using either an open or percutaneous technique. The

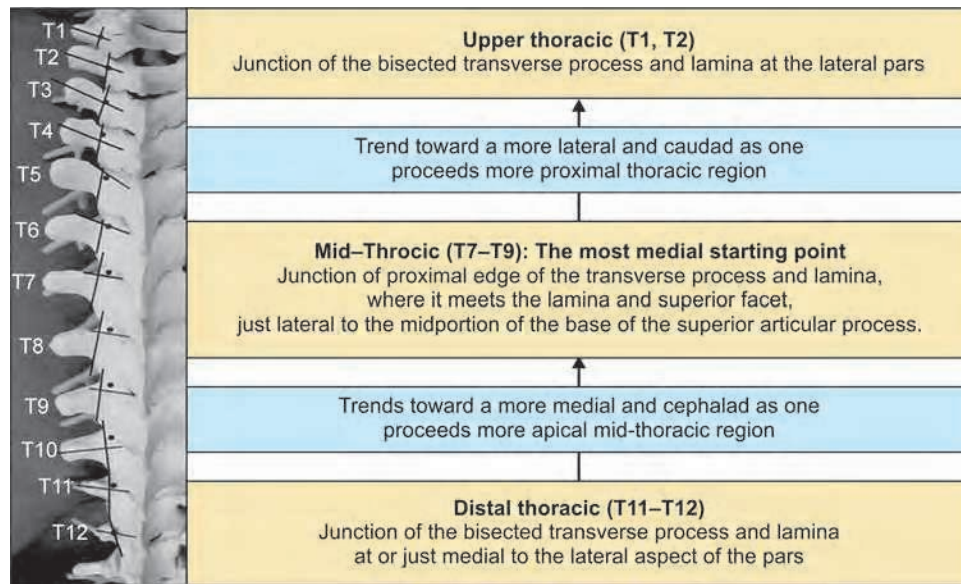
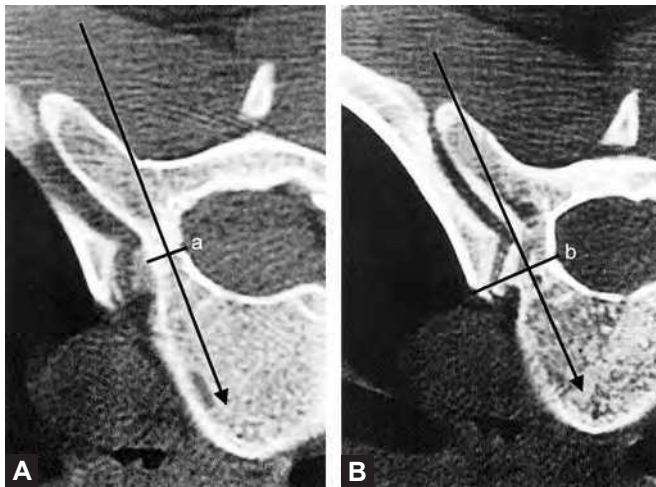


Fig. 99.1: On the left is a thoracic spine model with straightforward pedicle entry points indicated with black dots and black lines indicating the relationship with the transverse process and pars interarticularis. The text boxes indicate the trends related to the starting points. *Source:* Adapted from Kim YJ, Lenke LG, Bridwell KH, et al. Free hand pedicle screw placement in the thoracic spine: is it safe? *Spine (Phila Pa 1976)*. 2004;29(3):333-42.³⁵



Figs. 99.2A and B: Transverse cuts of a computed tomography scan at the level of a pedicle in the thoracic spine demonstrate the trajectory and relative width (a) of the thoracic pedicle (A) versus the width (b) of the pedicle/rib head complex (B).

Source: Adapted from O'Brien MF, Lenke LG, Mardjetko S, et al. Pedicle morphology in thoracic adolescent idiopathic scoliosis: is pedicle fixation an anatomically viable technique? *Spine (Phila Pa 1976)*. 2000;25(18):2285-93.⁴⁵

starting hole is then created and a thoracic pedicle gear-shift is advanced using intermittent images. After the pedicle screw path is created and confirmed fluoroscopically, the pedicle is tapped and a screw is placed.³⁶ In

recent years, CT-navigated pedicle screw placement has emerged and continues to gain popularity. This technique involves intraoperative CT after the patient is positioned followed by computer-generated guidance on the appropriate starting point, angle, and placement. CT scans can also be used in order to generate a three-dimensional (3D) computer-generated model preoperatively that is used in conjunction with the patient's anatomy in order to identify ideal starting points.³⁷

When placing thoracic pedicle screws, the trajectory of the screw is just as important as the proper starting point. In the transverse plane, the T1 thoracic pedicle is medially angled 28.2°; this decreases progressively to 8.2° at T12.³⁸ In the sagittal plane, the thoracic pedicles are angled downward the most at T2, 18.9°, and this decreases gradually as one proceeds caudad, to 10.7° at T12.³⁸ The intended path of the pedicle screw is also a point of debate. Many surgeons prefer to use the straightforward technique in which the pedicle screw is angled straight into the vertebral body just under the superior endplate, whereas others prefer the anatomic technique in which the pedicle screw is inserted parallel to the orientation of the thoracic pedicle.³⁹ Lehman et al.⁴⁰ demonstrated significantly higher maximal insertional torque and pullout strength in straightforward versus anatomic thoracic pedicle screws. Future research must elucidate the best thoracic pedicle screw trajectory.

Once a thoracic pedicle screw is placed, confirming accurate screw placement is generally recommended using fluoroscopy and/or triggered electromyography (EMG). Fluoroscopy is a common method to confirm screw placement but has limitations, especially in deformity where obtaining images orthogonal to the plane of the spine can be difficult. Upper thoracic pedicle anatomy can also be particularly difficult to visualize well using fluoroscopy, given the proximity of the shoulders. Triggered EMG is also frequently employed to test pedicle screws after placement. If the pedicle has a breach, the current will be transmitted through the pedicle screw to the nerve root at low amplitudes. One group uses triggered EMG values <6.0 mA as an indication that the pedicle screw may have a medial breach.³⁵ Other investigators have suggested different thresholds in deformity surgery. de Blas et al.⁴¹ demonstrated that different thresholds for triggered EMG should be used on the concavity versus the convexity in thoracic pedicle screws placed for deformity because of the displacement of the spinal cord toward the concavity of the spine. On the concavity, triggered EMG values of < 8.0 mA were an indication of medial breach whereas values > 14 mA indicated an intraosseous screw. On the convexity, triggered EMG values < 11 mA indicated a medial breach whereas values > 19 mA confirmed an intraosseous screw. Despite these findings, the authors concluded that triggered EMG has low sensitivity for detecting pedicle screws with a medial breach.⁴¹ The utility of triggered EMG is especially difficult proximal to T6 because of the problems associated with measuring EMG activity in the intercostal muscles versus the rectus abdominus.^{35,42}

The technique used for thoracic pedicle screw placement is at the discretion of the surgeon. The costs as well as time associated with using intraoperative CT navigation techniques have limited its widespread use. The authors prefer to use the freehand technique, as described by Kim et al.³⁵

Thoracic Pedicle Anatomy

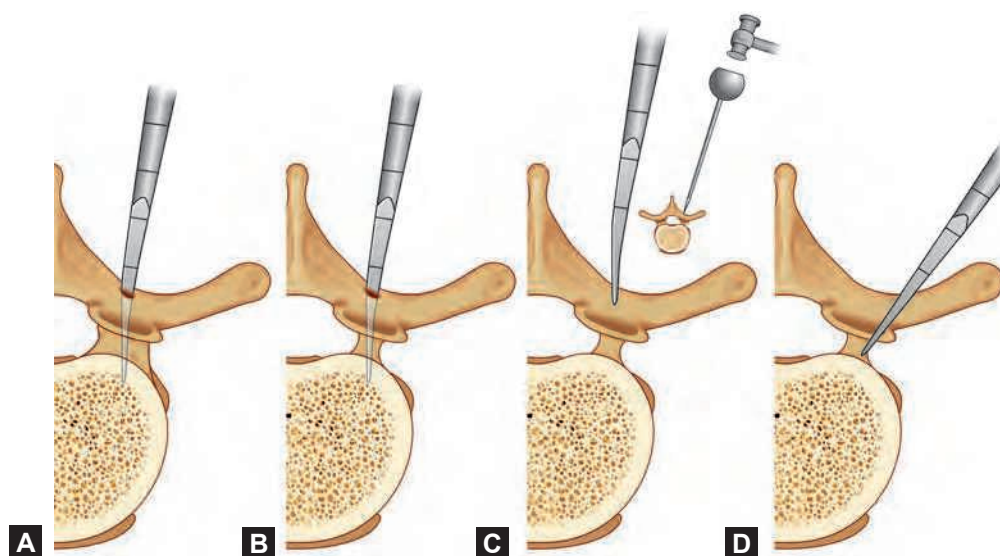
Because of the increased use of thoracic pedicle screws, many researchers have conducted investigations of the detailed anatomy of thoracic pedicles. Kothe et al.⁴³ performed a cadaveric study in which they demonstrated that the medial pedicle wall is 2–3 times thicker than the lateral wall. Furthermore, they showed that the cancellous channel is approximately two-thirds of the outer pedicle height and width. Ugur et al.⁴⁴ did an extensive analysis of the

thoracic pedicle dimensions, nerve root dimensions, and nerve root exit angle. Because of significant variation in thoracic pedicle size, they recommended detailed analysis of a CT scan preoperatively before placing thoracic pedicle screws.⁴⁴ In another thoracic pedicle anatomic study, O'Brien et al.⁴⁵ noted the significantly increased width of the thoracic pedicle/rib head complex (12.6–17.9 mm) compared to the thoracic pedicle width (4.6–8.25 mm). The authors noted that, in thoracic pedicles with severely narrowed pedicular width, an in-out-in technique could be utilized for thoracic fixation whereby the pedicle screw can start in the pedicle, pass laterally at the pedicle/vertebral body junction, and then insert back into the lateral vertebral body (Figs. 99.2 and 99.3, from Obrien 2000).⁴⁵ By using this method, surgeons can achieve segmental fixation in thoracic segments that have severely narrowed pedicles.

Thoracic pedicle anatomy can be varied in patients without deformity, but patients with coronal deformity are noted to have significant variations in pedicular size, especially on the concave side of the curve. To this end, Watanabe et al.⁴⁶ performed an extensive evaluation of 1,021 thoracic pedicles instrumented during scoliosis surgery in 53 patients. They classified the pedicles based on the cancellous channel: type A—Large cancellous channel with pedicle probe passing easily; type B—Small cancellous channel with pedicle probe passing snugly; type C—Cortical channel requiring the surgeon to tap the pedicle probe with a mallet in order to advance; and type D—Slit/absent pedicle requiring a juxtapedicular screw position (Figs. 99.1 and 99.3; Watanabe, 2010). The authors also noted that 90% of the thoracic pedicles in the study population had a cancellous channel (type A or B) and 7% had cortical channels (type C). On the convexity, 98.2% of the pedicles had cancellous channels, whereas 81.5% of the pedicles on the concavity had cancellous channels.⁴⁶ This information is important when planning thoracic pedicle fixation in deformity surgery.

Accuracy

Over the past 20 years, multiple investigators have examined the accuracy of thoracic pedicle screw placement. The most useful data from the literature regarding accuracy come from studies with patients who have been treated with thoracic pedicle screws and had a CT scan postoperatively. When examining this accuracy data, one must carefully note the definition of an inaccurately placed thoracic



Figs. 99.3A to D: Classification of thoracic pedicle morphology according to Watanabe et al.⁴⁶ Parts (A) and (B) demonstrate thoracic pedicles with cancellous channels. Part (C) has a cortical path requiring a mallet in order to create a pedicle channel, whereas part (D) has a slit morphology that requires a juxtapedicular pedicle screw position.

Source: Adapted from Watanabe K, Lenke LG, Matsumoto M, et al. A novel pedicle channel classification describing osseous anatomy: how many thoracic scoliotic pedicles have cancellous channels? *Spine (Phila Pa 1976)*. 2010;35(20):1836-42.⁴⁶

pedicle screw. Some authors with strict criteria will define any cortical breach as a miss, whereas most will only define an inaccurately placed pedicle screw as outside the “safe zone.” The safe zone was originally described by Gertzbein and Robbins,⁴⁷ who defined a 4-mm zone around the pedicle that was composed of 2 mm each of epidural space and subarachnoid space. Some have questioned this notion because of cadaveric studies⁴⁸ and anecdotal observations that the spinal cord is directly adjacent to some pedicles, especially on the concave side in coronal deformity. Nevertheless, Belmont et al.⁴⁹ defined < 2 mm as a reasonable medial safe zone whereas lateral pedicle wall violation had a higher tolerance up to 6 mm because of the presence of the rib head to protect the lung pleura. In large series’ reporting thoracic pedicle screw accuracy, only two report a neurologic deficit as a result of an errant pedicle screw and both had > 4 mm medial encroachment.⁴⁷⁻⁵⁰

Modern era studies report thoracic pedicle screw accuracy rates of 1–12.7%.^{6,35,36,49-54} The majority of these studies consider pedicle breaches that are within the safe zone to be accurately placed. This is appropriate given the inherent safety of the screws placed within this zone. Belmont et al.⁴⁹ performed an extensive analysis of 279 thoracic pedicle screws in 40 patients who were evaluated

postoperatively with CT scan. Using a freehand technique, the authors reported a 99% accuracy rate with a defined safe zone < 2 mm medially and < 6 mm laterally. In a large study, Suk et al.⁶ examined 4,604 thoracic pedicle screws and reported an accuracy rate of 98.5%, although it should be noted that not all patients were evaluated with a post-operative CT scan. Another investigation of 577 thoracic pedicle screws defined a missed pedicle screw as one in which the central axis of the screw was out of the pedicle.³⁵ They demonstrated an accuracy rate of 93.8%. More recent studies have reported accuracy rates of 97%,⁵³ 98%,⁵⁴ and 94.9%.⁵⁰ These data demonstrate that, using modern techniques, thoracic pedicle screws can be accurately placed in patients who require segmental thoracic spinal fixation.

Biomechanics

Biomechanical studies have demonstrated factors that are important when using thoracic pedicle screws in order to maximize the stability of thoracic pedicle screw constructs. Kuklo et al.⁵⁵ tested the maximal insertional torque of thoracic pedicle screws by using a tap that was the same diameter, 0.5-mm smaller, or 1.0-mm smaller than the diameter of the pedicle screw. They demonstrated that undertapping the pedicle by 1.0 mm improved pedicle screw maximal insertional torque.⁵⁵ In another cadaveric study, Deviren

et al.⁵⁶ showed that more thoracic pedicle screws are required for stability if there is preoperative instability or instability created intraoperatively. In deformity patients, a thoracic pedicle screw placed using the “in-out-in” technique for dysplastic pedicles has been demonstrated to have 75% of the pullout strength of an intrapedicular screw.⁵⁷ Moreover, there is a drop in biomechanical strength when a breach occurs while trying to place a straightforward thoracic pedicle screw, and it is salvaged with an anatomically placed thoracic pedicle screw.³⁹ Additionally, Paxinos et al. demonstrated the importance of bone mineral density in thoracic pedicle instrumentation.⁵⁸ They showed that the pullout force of any posterior thoracic instrumentation in osteopenic bone was one-fourth the strength of the same instrumentation in normal bone.⁵⁸ In the setting of pedicle screw fixation in osteoporotic bone, pedicle augmentation with polymethylmethacrylate prior to screw placement has been found to increase biomechanical fixation⁵⁹ and potentially improve results.⁶⁰

CLINICAL UTILITY

Outcomes

The majority of the outcomes related to the use of thoracic pedicle screws are in deformity patients. Overall, thoracic pedicle screws allow for an improved correction of the coronal deformity, but patient outcomes using validated instruments have failed to show significant differences between pedicle screws and alternative instruments. An early study clearly documented the improved deformity correction using all pedicle screw constructs, but the authors did not report validated patient-reported outcomes.⁶¹ In a more recent study, Lehman et al.⁶² reported the intermediate-term outcome of adolescent idiopathic scoliosis and demonstrated the following corrections: 68% for the main thoracic, 50% for the proximal thoracic, and 66% for the thoracolumbar/lumbar curve at final follow-up. They also reported Scoliosis Research Society (SRS) scores of 83% at final follow-up. In another retrospective cohort study, Di Silvestre et al.¹² compared adolescent idiopathic scoliosis (AIS) patients treated with pedicle screw-only constructs versus hybrid constructs and demonstrated improved curve correction but no difference in the SRS-30 Health-Related Quality of Life or Short Form-30 outcomes. Others have mirrored these results.^{10,11,13,14,63}

Some of the most important data related to the use of thoracic pedicle screws is the avoidance of anterior

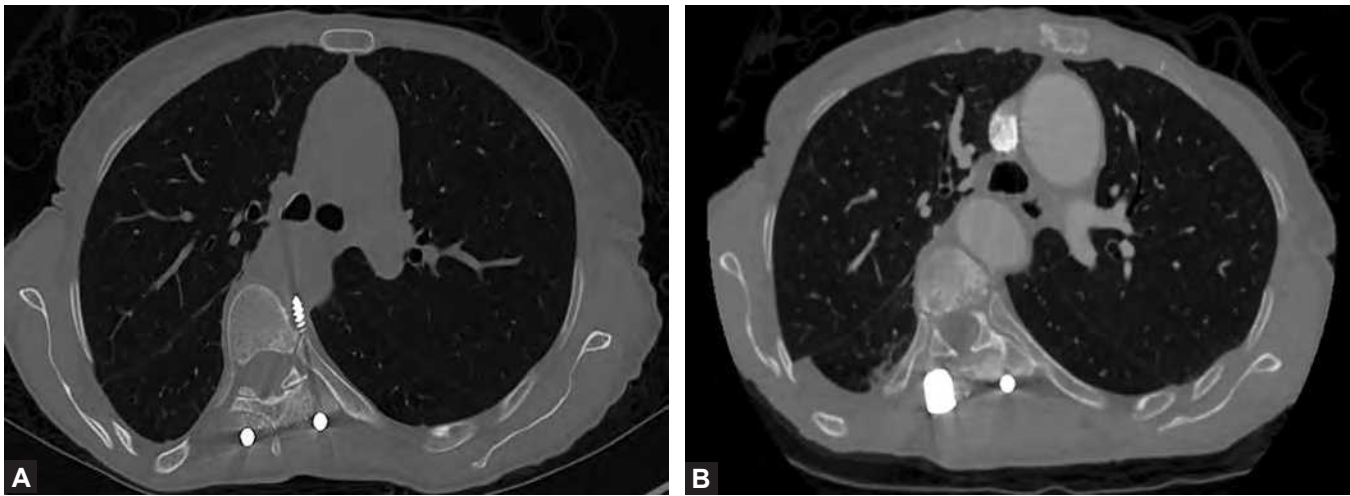
procedures in deformity patients. A classic study showed that anterior procedures negatively affect postoperative pulmonary function in deformity patients.¹⁸ Thoracic pedicle screws have allowed surgeons to avoid violation of the thoracic cavity because of the significant biomechanical advantage offered by three-column fixation. In a direct comparison of all-anterior versus all-posterior surgical approach for Lenke 5C scoliosis, Geck et al.¹⁶ demonstrated shorter hospital stays and better and stable curve correction at a minimum of 2 years. The avoidance of an anterior approach in the thorax may be one of the most compelling reasons to utilize thoracic pedicle screws.

There is a paucity of reported outcomes for the use of thoracic pedicle screws in trauma, degenerative conditions, infection, and tumor surgery. The authors of one retrospective thoracolumbar trauma series reported 12.7% pedicle screw breach (or failure) rate, with no complications related to the missed screws.³⁶ In this series, there were four complications, but only one related to rod breakage. Despite extensive use of thoracic pedicle screws in other surgical conditions requiring thoracic fixation, there is minimal data on outcomes related to their use.

Complications

When thoracic pedicle screws were first introduced, one of the main concerns was the risk of injury to surrounding neurologic and vascular structures. Given the close proximity of these structures,^{44,48} this concern is valid. Other structures, such as the lung and esophagus, are also at risk when placing thoracic pedicle screws. Li et al.⁶⁴ performed a retrospective review of complication rates in 208 deformity patients who were treated with 1,123 thoracic pedicle screws. They reported a complication rate of 16.5%, which they categorized as either directly or indirectly related to the pedicle screws (Table 99.1).⁶⁴ Other large retrospective series examining thoracic pedicle screws have reported complication rates. Suk et al.⁶ reported 67 screw malpositions (1.5%) in 48 patients (10.4%) and Kim et al.³⁵ reported 36 screw malpositions (6.2%; Table 99.1).

The results from these large retrospective cohort studies demonstrate that the most common complications related to thoracic pedicle screws in deformity patients are aberrant screw placement and cerebrospinal fluid leaks. Despite the screw malpositions that were reported, these studies demonstrated only two transient neurologic complications, with no vascular or visceral complications (Table 99.1). The infection rates in these studies are not



Figs. 99.4A and B: Computed tomography (CT) scan demonstrating a malpositioned thoracic pedicle screw with the tip of the screw abutting the descending thoracic aorta (A). After removal of the screw secondary to patient complaints of an ipsilateral thoracic radiculopathy related to the pedicle screw, CT angiography displays subtle dye leakage and pseudoaneurysm of the aorta (B). The patient developed abdominal pain postoperatively that was attributed to mesenteric ischemia secondary to thromboembolic disease. The patient's abdominal pain was completely relieved after 48 hours of anticoagulation with heparin.

directly related to thoracic pedicle screw instrumentation, as similar rates are likely to have occurred using alternative thoracic fixation techniques. Vascular complications have been reported in other small series and case reports⁶⁵ as well as anecdotally (Figs. 99.4A and B: CT angiography

of a recent Cheng patient with a screw in the aorta). Despite these reports, multiple large series in the literature demonstrate a very low incidence of complications related to the use of thoracic pedicle screws.

Complications seen with longer follow-up are also important. A short retrospective series detailed proximal junctional vertebral fracture or subluxation in 10 patients who underwent adult deformity surgery³⁰. These can be catastrophic failures because two patients with fracture of the proximal level and vertebral subluxation one level above had Frankel B neurologic injuries as a result of the injury. The authors noted that old age, osteopenia, preoperative comorbidities, and severe preoperative global sagittal imbalance were risk factors for this complication.³⁰ It is possible that the superior biomechanical fixation provided by thoracic pedicle screws allowed for greater correction of the deformities but predisposed these patients to proximal junctional failure.

There is a risk profile associated with the use of thoracic pedicle screws. Despite the risk profile, these techniques can be employed safely and the risks can be minimized with careful indications, decision-making, and surgical techniques.

CONCLUSION

Thoracic pedicle screws are important in modern spine surgery. They allow for three-column fixation of the thoracic

Table 99.1: Complications related to the use of thoracic pedicle screws.

	<i>Li et al.</i> ⁶⁴	<i>Kim et al.</i> ³⁵	<i>Suk et al.</i> ⁶
Patients	208	45	462
Pedicle screws	1,123	577	4,604
Overall complication	16.5%	NR	13.3%
Malpositioned pedicle screws			
Number of (%) patients	15 (7.2%)	NR	48 (10.4%)
Number of (%) pedicle screws	19 (1.7%)	36 (6.2%)	67 (1.5%)
Dural tear	3 (1.4%)	"Several"	3 (0.6%)
Pedicle fracture	2 (0.9%)	0	11 (NR)
Screw loosening	3 (1.4%)	0	35 (NR)
Neurologic	1 (0.4%)	0	1 (0.2%)
Vascular	0	0	0
Infection	8 (3.8%)	0	9 (1.9%)
Pulmonary	3 (1.6%)	0	1 (0.2%)
Visceral	0	0	0

(NR: Not reported).

spine, thereby allowing for greater correction in deformity surgery and greater stability in trauma, degenerative, tumor, and infection. There are several advantages and disadvantages to using thoracic pedicle screws that are relevant in the surgical treatment of a thoracic spine condition. If surgeons are thoughtful in their use of thoracic pedicle screws, the advantages can outweigh the disadvantages. Surgeons are increasingly more competent with the use of thoracic pedicle screws, given the frequency with which they are used. Several techniques exist for placing thoracic pedicle screws. Each surgeon should use the technique that is the most effective and efficient in his or her own hands. In this way, patients can have improved outcomes after thoracic pedicle screw instrumentation while minimizing the risk of complications.

KEY POINTS

- Thoracic pedicle screws provide greater correction and stability than other types of fixation through three-column fixation.
- Thoracic pedicle screws have concomitant drawbacks including risk of proximal junctional kyphosis, potential neurologic and vascular complications, and increased cost.
- A thorough understanding of thoracic spine anatomy and pedicle morphometry is necessary for safe placement of screws in this region.

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Direct Lateral Thoracic Interbody Fusion

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Snapshot

- » Surgical Approaches
- » Positioning
- » Approach
- » Entering the Spinal Canal
- » Working Inside the Canal
- » Reconstruction, Instrumentation, and Closure

INTRODUCTION

During the last few decades, the development of powerful implants, the introduction of the microscope/endo-scope, and intraoperative real-time three-dimensional imaging have positioned spine surgery at the cutting edge of technology. Since the early 1990s, different surgical approaches have been published using “less invasive access techniques,” based on the premise of minimizing damage to functional tissue in order to avoid associated morbidity without compromising the goals of the surgery.¹ This process has compelled the practitioners of minimally invasive spine surgery (MISS) to prove that less invasive procedures are at least as safe and effective as “gold standard” open procedures.

SURGICAL APPROACHES

Among the anterior thoracic approaches, both the transpleural and the retropleural^{2,3} techniques are commonly used. Anterior exposures have the following advantages over their posterior-based counterparts:

- Directly addresses the affected lateral side
- Keeps most structures important for spinal stability intact
- Higher fusion rate due to relatively large endplate surface area
- Better visualization of the spinal canal with negligible dural sac manipulation.

POSITIONING

The patient is positioned straight laterally, ensuring that the spine lies parallel to the table and securely fixed. Using the C-arm, the surgeon carefully identifies the surgical level. The surgical level should be identified prior to the approach and, again, before any work on the spine begins.

A given approach can be performed from either side. When approaching from the patient’s right side, one must keep in mind that the dome of the diaphragm may obscure the view of the lower thoracic levels and must be held out of the operative field. However, the right side offers a wider working area, especially in the upper and middle thoracic regions, because the aorta and the thoracic duct are located on the left. Therefore, the left-sided approach is often preferred at lower thoracic levels as the diaphragm is more easily kept out of the surgical field and the lateral decubitus position allows the kidney and spleen to move anteriorly (Fig. 100.1). The aorta and thoracic duct lie anteriorly in the midline, leaving the lateral aspect of the spine freely accessible.

APPROACH

Preoperative skin marking varies somewhat according to the shape of the thorax and rib angulation. The incision is typically made two intercostal spaces superior to the

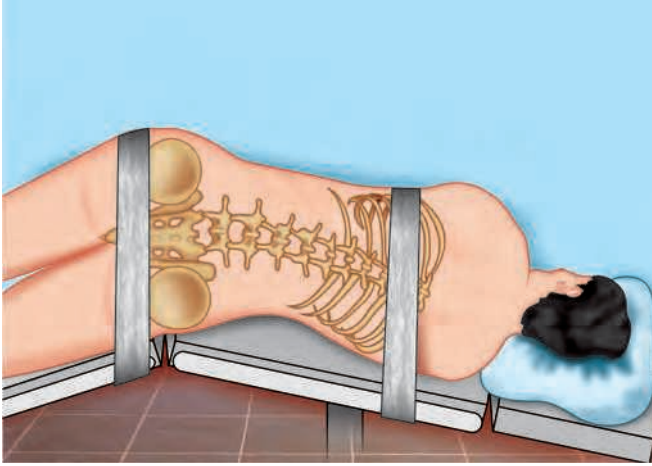


Fig. 100.1: Lateral decubitus patient positioning.

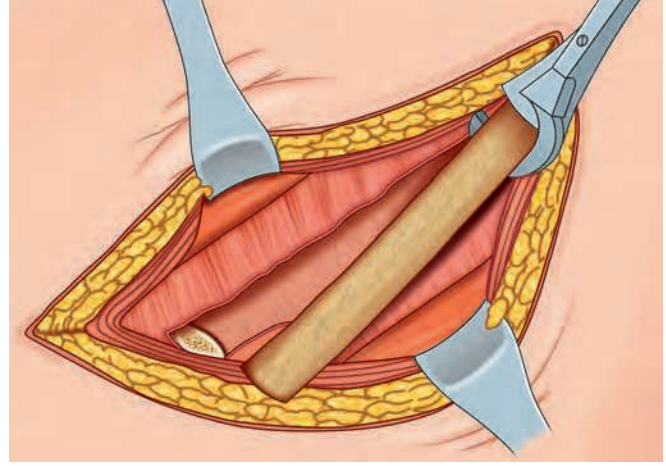


Fig. 100.2: The rib is sectioned after subperiosteal dissection.

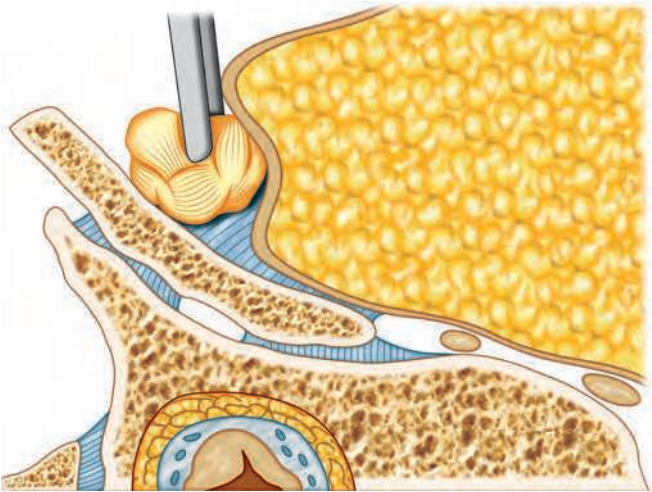


Fig. 100.3: The pleura is intact and the rib stump is detached from the thoracic wall.

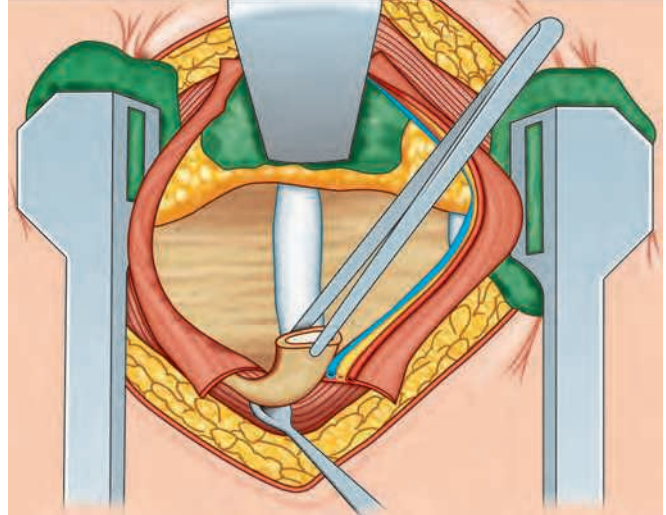


Fig. 100.4: Retractors in place.

targeted vertebral body or disc space.⁴ The muscle layers are divided parallel to the skin incision until the underlying rib is exposed over a length of 8–10 cm. From this step onward, the transpleural technique splits the pleura parallel to the ribs. After the lung is collapsed, a rib spreader is used to enlarge the intercostal space and open the chest cavity to expose the spine.

The retropleural approach is technically more demanding. After uncovering the rib, the periosteum is dissected and elevated followed by detaching the pleura and endopleural fascia from the deep costal surface, taking care not to violate the pleura (Fig. 100.2). The neurovascular bundle is isolated from the undersurface of the lower border of the rib. A single- or double-“window” osteotomy

of the rib is performed. Resection of two ribs may be performed for a wider field of view or when the surgeon plans to use the rib for structural autograft.

After displacing the rib cranially or caudally or removing it completely, the endopleural fascia is divided and the parietal pleura is elevated from the thoracic wall, thus entering the retropleural space. Further dissection down to the head of the rib and vertebral body is performed using finger or instrument dissection, taking care to avoid direct pressure against the fragile pleura, which can be easily disrupted (Fig. 100.3). Once the exposure is complete, a self-retaining retractor is placed. The detached pleura and the deflated lung are gently retracted anteriorly allowing visualization of the spinal column and the affected segment (Fig. 100.4).

As the surgical field is relatively small, some source of illumination and magnification is required in order to visualize the anatomy properly. In addition to a light source, a surgical microscope or endoscope can be used.⁵

■ ENTERING THE SPINAL CANAL

Using a combination of clues from preoperative imaging, anatomical landmarks, and intraoperative imaging, the surgeon can now begin with the planned decompression. Anatomically, the anterior border of the spinal canal is made up of the posterior wall of the vertebral body, the posterior annulus fibrosus, and the posterior longitudinal ligament. The lateral boundary is defined by the intervertebral foramen, which is covered by the costal head between the second and tenth thoracic vertebrae.⁶ Uncovering the foramen is the quickest, simplest, and safest way to gain access to the spinal canal. Exceptions to this include conditions such as discitis or tumors that can cause destruction of the normal canal boundaries.

Rib head removal can be performed with a burr, an oscillating saw, or an ultrasound device such as a bone scalpel. Once the foramen is free, the portion of the pedicle caudal or cranial to the disc can be removed to further uncover the dura.^{7,8} Care must be taken to minimize venous bleeding from elevated pressure in the compressed epidural venous plexus; such bleeds can often be stopped with gentle pressure using a fibrin sponge or other hemostatic agents. If a complete vertebrectomy is not planned, there is no need to ligate the segmental arteries as they rarely interfere. When resecting a large intracanal mass-occupying lesion, it may be necessary to perform a partial vertebrectomy of the posterior aspect of the neighboring vertebrae extending as far cranially, caudally, or medially as necessary.⁹ In the case of a vertebral body resection, the vertebrectomy can be performed once the segmental arteries have been ligated. By doing so, the exposure is enlarged, gaining wider access to the ventral portion of the canal and helping to ensure that the surgeon will not place unnecessary pressure on the already compromised spinal cord.

■ WORKING INSIDE THE CANAL

Once a partial corpectomy defect has been created, the surgeon can focus on dissecting and resecting any pathologic process by drawing it into the ventral defect. When removing bone or a calcified disc, care should be taken to remove fragments under careful control as sudden release

and a snapping back of tethered fragments will percuss the cord, resulting in a spinal cord contusion and bleeding that may lead to a neurologic deficit. The posterior longitudinal ligament is divided as necessary for further access to the thecal sac. In long-standing pathology or calcified processes, the ligament can be very adherent to the dura, making detachment tedious and possibly leading to a dural tear. Epidural bleeding is often an indirect sign that cord compression still exists. Bleeds can be controlled using either bipolar forceps or small pieces of gel foam placed between the dura and the anterior margin of the canal. Dural pulsation and lack of epidural bleeding are signs that complete decompression has been achieved.

■ RECONSTRUCTION, INSTRUMENTATION, AND CLOSURE

Following a discectomy with minimal bony resection, reconstruction may only require the placement of a structural bone graft. In most cases, this will not require the addition of instrumentation; the vertebrae and spinal canal will remodel and achieve stability simply with a bone graft reconstituting the surgical defect.¹⁰ When an extensive resection or vertebrectomy has been performed, the anterior spinal column must be reconstructed in order to maintain its load-bearing capacity. The technique used for this procedure has been previously described.¹¹⁻¹³ Briefly, a thorough decompression is performed using burrs, curettes, osteotomes, and pituitaries. Next, an interbody spacer consisting of a metallic or polymer cage—fixed or expandable—or an allograft or autograph bone strut is selected. For reconstruction after infection, an autologous structural iliac crest strut is often preferred. An expandable cage may be used and introduced into the cavity and progressively distracted until adequate distraction of the interspace is accomplished. Fixed cages or structural bone grafts must be carefully selected or reshaped to fit the space that exists for an optimum press fit. Anterior instrumentation with plates and screws may be added to reinforce the spine's load-bearing capacity and to protect the implant from subsidence or expulsion until fusion has been achieved, especially if no posterior instrumentation is used.

Closure of the operative site may then be initiated. After placing a drain, the lung is ventilated and re-expanded, pushing the parietal pleura back to its natural position. The soft tissue is then closed in layers (Fig. 100.3). If not used for reconstruction, the resected rib may be replaced and fixed using either absorbable stitches or titanium mini-plates.

DISCUSSION

Is the Term “Direct Lateral Approach” Appropriate for the Thoracic Spine?

During the last couple of decades, the extreme lateral or direct lateral approach was popularized for the treatment of lumbar spine disorders.¹⁴ These techniques either split or retract the psoas muscle fibers while avoiding injury to the lumbar plexus in order to reach the spine.¹⁵ By revamping older approaches¹⁶ and using modern instruments (i.e. expandable tubular retractors), surgeons have adapted this technique for the thoracic region, keeping the term “direct lateral” (Fig. 100.4). When approaching the thoracic spine, there is no muscle overlying the lateral aspect of the spine above the proximal extent of the psoas muscle, which originates from the transverse process of T12. In a strict sense, all approaches to the thoracic vertebral bodies must be considered a “direct lateral” technique. These include the transthoracic transpleural (including mini-thoracotomy), thoracoscopic, and retropleural approaches (Fig. 100.5).

Rationale for an Anterior Approach

The aim of any type of surgery is to achieve optimal results while minimizing what has been termed “approach-related trauma.”¹⁷ Spinal stability is based on three pillars: integrity of the spine and supporting structures, neurologic status, and pain level. In modern spine surgery, attention to preserving quality and function of the injured tissue plays a major role. Direct approaches to the anterior thoracic spine aim to reduce soft tissue trauma and risk of injury to the neural elements.

Surgical decompression and reconstruction techniques of the thoracic and thoracolumbar spine have undergone a dramatic evolution during the last few decades. Forty-four years ago, Perot described a thoracotomy for the treatment of degenerative disease of the spine.¹⁸ The unobstructed view of the thecal sac provided by this technique remains the most reliable method for achieving decompression in the patient with a neurologic deficit due to a space-occupying lesion within the spinal canal. During the last 20 years, various anterior procedures have gained widespread acceptance in cases where anterior column reconstruction, or correction of collapsed or kyphotic segments, is needed to restore the load-bearing function of the spine.¹² The anterior approach has also been

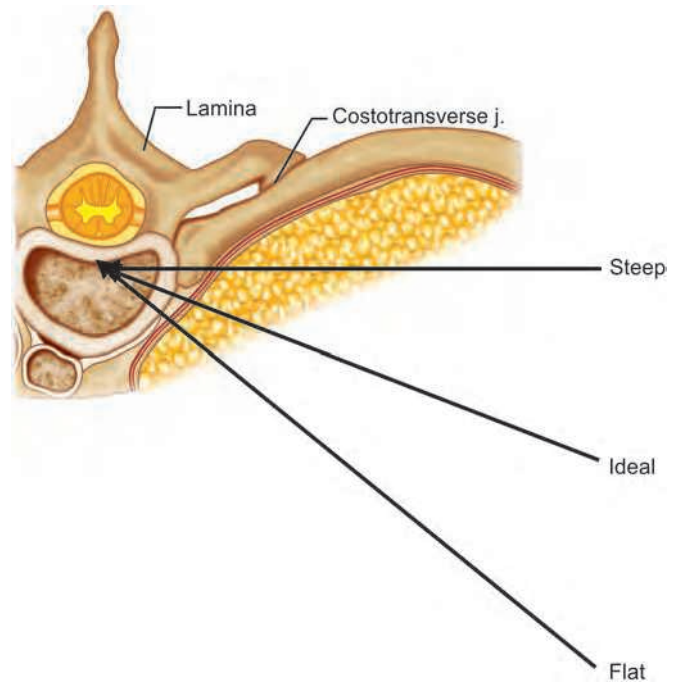


Fig. 100.5: Angle of approach.

particularly useful in the treatment of fixed thoracolumbar scoliosis.¹⁹ Anterior release increases the flexibility of the spine in patients with rigid curves and facilitates segmental correction. This can be accomplished using either intervertebral grafts or posterior reduction maneuvers for staged procedures to improve sagittal and coronal correction while minimizing the number of fused levels.²⁰

Compared with the transpleural approach to the thoracic spine, the notable differences with the retropleural approach are the wound size as well as the extent of damage to the diaphragm. Complications such as paralysis of the diaphragm and atelectasis can occur after iatrogenic diaphragmatic injury.²¹ The pleura often acts as a natural barrier between a neoplasm or infectious focus and the pleural cavity.^{22,23} Surgery performed with less invasive techniques may mitigate such complications by limiting collateral damage to the surrounding soft tissues. Rosenthal et al. demonstrated a significantly lower level of infection in MISS cases compared to open.²⁴ There is, however, limited evidence to suggest that results using smaller incisions or less aggressive exposures are superior to the open approach. Nevertheless, it stands to reason that unnecessary approach-related tissue injury should be minimized whenever possible, provided surgical outcomes are equivalent.

Advantages of Direct Lateral Approach

- Approaches from the side of pathology
- Wider surface to achieve fusion compared to posterior procedures
- Decreased amount of time with prolonged lung deflation with MISS techniques compared to traditional thoracotomy²⁵
- Decreased need for a thoracic surgeon due to lower risk of injury to vasculature
- Three options to perform the approach (retropleural, mini-open, and thoracoscopic)
- Continuous visualization of anterior structures and of the spinal cord
- Potential for less perioperative morbidity and trauma to patient compared to traditional thoracotomy²⁴

Disadvantages

- Not suited for the upper thoracic level (above T3) due to the shoulder-clavicular complex
- Steep technical learning curve

Although posterior approaches have also been tailored to the use of retractors and percutaneous systems, muscle and bony surgical injury are often more extensive than with anterior techniques.

CONCLUSION

In 1987, Wickham published the first paper defining the term “minimally invasive” as “minimal damage of biologic tissue at the point of entrance of surgical instruments.”²⁶ Almost 20 years later, Seldomridge attempted to explain the term “minimally invasive spine surgery”: “The primary goal of minimally invasive spinal surgery is to minimize paraspinal muscle retraction and dissection in the hope that this will lead to reduced blood loss and postoperative pain, acceleration of the recovery period, and improve clinical outcomes.”²⁷ The primary goal of less invasive surgery is the reduction in tissue damage and functional damage to the motion segment in order to minimize postoperative pain, use of analgesics, and blood loss. These goals must always remain secondary to achieving comparable or superior results versus traditional techniques.

It is in human nature to continuously examine all aspects of treatment scientifically, to attempt to push the envelope further, and to improve results and reduce

patient's risk. Keep in mind Ford's quote as it pertains to spine surgery, implying that innovation is not necessarily better or worse, but rather a different way to solve a given problem.

KEY POINTS

- The patient is placed in the lateral decubitus position on the same side as the disc herniation or space-occupying lesion. The skin incision is made two disc levels above the pathology, and entry is gained into the thorax just above the superior edge of the rib
- To gain access to the spinal canal, costal head resection followed by pediculectomy of the cranial and/or caudal segments results in better visualization of the dura
- With MISS, there is reduced ability to address many spinal levels compared to an open thoracotomy, but the reduced soft tissue damage may be of benefit in patients with significant medical comorbidities²⁸
- The direct lateral approach avoids the extensive muscle dissection associated with posterior approaches and provides a direct view of anterior or lateral pathology²⁴
- The direct lateral approach provides the same exposure as traditional thoracotomy exposures, but does not require single lung ventilation, a large incision, or extensive rib resection²⁹

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- Provides evidence-based medicine results of indicated surgery in a patient subset.
- Perot PL Jr, Munro DD. Transthoracic removal of midline thoracic disc protrusions causing spinal cord compression. *J Neurosurg.* 1969;31:452-8.
- This article provides information on performing transthoracic and retroperitoneal approaches and describes the benefits of direct lateral approaches over thoracotomy

SECTION

11

Pediatrics

S Rajasekaran



Back Pain in Children and Adolescents

Yan Wang, Hui Liu

Snapshot

- » Definition of Back Pain in Children
- » History
- » Physical Examination
- » Laboratory Evaluation
- » Radiographic Evaluation
- » Special Clinical Entities
- » Bone Tumors
- » Psychosomatic Pain

INTRODUCTION

Back pain in the pediatric age is an uncommon clinical complaint and is significantly rare than in adults. In the absence of traumatic insult, back pain in children and adolescents frequently denotes serious underlying pathology. The one-year prevalence rate of low back pain in children has been reported from 7% to 58%.¹ Pain beyond duration of 3 weeks warrants careful and thorough investigation performed by clinical, laboratory, and imaging examinations. Describing difficulty, special stress world in childhood, and other psychosocial history should also be assessed.

DEFINITION OF BACK PAIN IN CHILDREN

Nonspecific back pain has been found as the most common type of back pain in children.² Visual analog scale seems to be still the most practical scale for measurement and follow-up of the intensity of pain in children. For limited reliability history from children or their parents, more validity and reliability scales for assessment of pain intensity in children are mandatory. Recently, some new standard scales for assessment of pain intensity in children with acceptable validity and reliability have been developed.^{3,4} FACES Pain Rating Scale³ that works on the basis

of the facial expressions and has been quantified in recent studies can also be used by the pediatricians to measure the intensity of the pain in children. For children of <7 years and >2 months, FLACC (Facial expression, Leg movement, Activity, Cry, Consolability) has been validated.⁴ After pain severity assessment, diagnosis of different categories should consist of an algorithmic clinical approach. Bunnell suggested mechanical, developmental, inflammatory, and neoplastic processes for lower back pain in pediatric patients.⁵ Rodriguez and Poussaint categorized the possible diagnosis in children (Table 101.1).⁶

HISTORY

Taking complete and accurate history is most important for the pathological diagnosis in the pain of children. In fact, difficulty answering basic clinical question and secondary history from parents may be the most obstacles in history recording.

The physician should ask the patients regarding the onset of symptoms, description of the pain characteristics including location, duration, presence or lack of radiation, and also exacerbating and alleviating factors. To differentiate between mechanical and inflammatory types of pain, the physician should ask the patients whether they have morning stiffness or reduction of pain after activity.

Table 101.1: Etiologies of low back pain in children and adolescents.

- I. More common musculoskeletal and mechanical etiologies
 - A. Nonspecific low back pain
 - Muscular strain
 - B. Special diagnosis
 - Spondylolysis/spondylolisthesis
 - Malalignment
 - Scheuermann disease
 - Scoliosis
 - Intervertebral disc herniation
- II. Other etiologies
 - A. Vertebral column fractures
 - B. Infectious diseases
 - C. Inflammatory
 - Ankylosing spondylitis
 - Juvenile idiopathic arthritis
 - Arthritis
 - D. Neoplastic disorders
 - Spinal column
 - Primary neoplasms
 - Secondary neoplasms
 - Spinal cord
 - Intramedullary
 - Extradural tumors
 - Intradural-extradural
 - E. Congenital and hematologic diseases

Inflammatory type of pain normally increases after prolonged rest and reduces by physical activity. Therefore, increase of pain intensity after walking for a long period of time implies more on mechanical pain. When taking history, the physicians should also think on some familial conditions and ask for family history of neurological and rheumatological diseases as well as congenital abnormalities. It should be emphasized that back pain may be a neurological symptom of the neurological system involved. Other neurological function-related message should be collected, such as walking distance, daily activity, extremity atrophy, numbness, muscle weakness, and so on.

PHYSICAL EXAMINATION

It is preferable to perform a complete physical examination in all the children with lower back pain (LBP). General surveys include general behavior, mannerisms, patients' details location, and severity of their symptoms. Sagittal alignment should be viewed from sided observation. Any skin anomalous should be recorded including hairy patches, pigmentation, dermal sinuses, and so on. Palpation should not only be focused on the reported pain

location, but also on whole spine. Pelvic examination should be performed, such as Thomas' test, Trendelenburg test, Patrick's test Flexion, ABduction, and External Rotation lower limbs for hip joint test (FABER), and Ober's test. Then a complete neurological examination should be performed in all children with LBP, necessarily strength and sensation in lower extremities and deep tendon reflex, to reveal any possible underlying intraspinal pathologies in these patients. The core stability of the children, as in the case of any weaknesses, and lack of coordination in paraspinal and lateral abdominal muscles should also be assessed. Some major clinical examinations that should be performed in the children with LBP are Adams's forward bending test, straight leg raise (SLR), or Lasegue test. Other joints are assessed for flexibility and range of motion. Secondary sexual characteristics should also be recorded for any developmental assessment and related endocrine system pathology.

LABORATORY EVALUATION

When suspicious, a systemic, inflammatory, or infectious process, complete blood count, erythrocyte sedimentation rate (ESR), serum C-reactive protein (CRP), rheumatoid factor, HLA-B27 test should be performed. While clinical circumstances indicate infection, blood and urine cultures are mandatory. Further chemical panel may be needed for causes of back pain.

RADIOGRAPHIC EVALUATION

Plain Radiograph

The plain radiographic evaluation of the spine is the basic and first radiographic examination for assessing lower back pain. Commonly, anteroposterior (AP) and lateral views are selected for screening. In the AP view, coronal alignment, symmetry and rotation of pedicle, width of pedicle, interpedicular and interspinous distance, and other bony structure of vertebral should be evaluated. Lateral view can accommodate message of alignment of sagittal spine, intervertebral disk, and integrity of endplate. Nonrotational scoliosis often indicates the pathological segment. If obvious scoliosis or kyphosis deformity is found in the lumbar spine X-ray or chest film, a full spine radiographic evaluation is indicated for a general alignment evaluation. Also coronal bending and lateral flexion and extension radiographs should be included for evaluating the flexibility of spinal deformity while the therapeutic

choice is required. Oblique X-ray is specially indicated for the suspicious pars pathology.

Radionuclide Bone Scanning and Single Photon Emission Computed Tomography Scanning

For more than 30 years, radionuclide bone scanning has been known as one of the most sensitive noninvasive methods to detect focal bone pathology. A key advantage is high sensitivity, higher than computed tomography (CT) or standard radiography. In the majority of nuclear medicine institutions, bone scans are currently obtained in whole-body technique using double-head γ camera systems equipped with high- or even ultrahigh-resolution collimators. Single-photon emission computed tomography (SPECT) is performed for focal abnormalities. This technique enables the accurate localization of tracer accumulations, especially in anatomical regions that are otherwise difficult to interpret because of complex architecture of skeletal structures such as the spine, pelvis, or skull.

The radiopharmaceutical most often used in bone scintigraphy is ^{99m}Tc -methylene diphosphonate. This compound binds to bone by chemisorption to the hydroxyapatite crystal. Two to six hours after intravenous injection, ~50% of the injected dose is accumulated in the skeletal system. Enhanced uptake (focally or diffusely) reflects increased bone turnover caused by changes of bone vascularization and/or osteoblastic activity.

Bone scanning with ^{99m}Tc -methylene diphosphonate detects abnormalities of bone metabolism as early as 24–48 hours after the onset of pathology. Thus, fractures and other manifestations of bone stress can be diagnosed very sensitively by bone scintigraphy.

On the other hand, bone scintigraphy can be used successfully in ruling out bone infection. If triple-phase bone scintigraphy is negative and vascular problems can be excluded, osteomyelitis is most unlikely. Nonetheless, leukocyte scanning using ^{111}In - or ^{99m}Tc -labeled leukocytes or granulocytes is still the gold standard to diagnose bone infection. It is known to be highly sensitive as well as specific.⁷ Recently, new multimodality imaging technique combining high-resolution structural images (CT) and functional radionuclide scan images (SPECT) has been developed. It is chiefly reserved for patients in whom the whole-body scan shows one or more images of unclear significance. This hybrid imaging

modality combines structural and functional images, which has considerably improved the imaging of patients with malignancies.⁸

Computed Tomography

Since CT introduced into clinical scenario, it has brought a large amount of diagnostic clues of bony pathology. Later evolution of computer techniques, three-dimensional (3D), super thin-sliced CT can figure out more specific trauma or pathological lesion. Computed tomography is also a helpful diagnostic tool for lumbar disc herniation and canal stenosis. Although magnetic resonance (MR) has brought more direct sensitivity for soft tissue pathology, CT is still superior to MR and plain X-ray for its high-quality bony lesion and 3D reconstructive views. For low back pain in childhood and adolescent, CT can demonstrate more diagnostic message in spondylolysis,⁹ bone lesion, congenital anomalous, and other bony pathology.

Magnetic Resonance Imaging

Magnetic resonance techniques have revolutionized the evaluation of low back pain in children and adolescents. The noninvasive and high sensitivity has made MR the first choice of most spine pathology. Magnetic resonance is very useful in demonstrating neurological structures and soft tissue around the cord. Common MR scan sequence includes T1, T2, spin echo, and fat echo, which provide ability to show contrast of different tissues. Another most used MR technique is T1 sequence with contrast agents, which help identify spinal tumor, separation of scar, and recurrent disc herniation.

According to different clinical entities, MR has different advantages. For disc degeneration diseases, not only it facilitates the assessment of neurological compressive condition, but also it can demonstrate the degree of degenerative process. Pfirrmann has divided the disc into five grades according to its structure, distinction of nucleus and annulus, signal intensity, and disc height,¹⁰ as listed in Table 101.2. Annulus tear can present high-intensity zone in MR T2 sequence, which is reported to be related to lower back pain and positive discography. Degenerative endplate can show modic changes, which are correlated with the prevalence of back pain, therapeutic strategy, and prognostic values.^{11–13} For spondylolysis, MR may bring messages of acute or chronic process of pars defect, which also has prognostic values of treatment. For spine infection, MR may indicate the severity of discitis,

Table 101.2: Classification of disc degeneration*.

<i>Grade</i>	<i>Structure</i>	<i>Distinction of nucleus and annulus</i>	<i>Signal intensity</i>	<i>Height of intervertebral disc</i>
I	Homogeneous, bright white	Clear	Hyperintense, isointense to cerebrospinal fluid	Normal
II	Inhomogeneous with or without horizontal bands	Clear	Hyperintense, isointense to cerebrospinal fluid	Normal
III	Inhomogeneous, gray	Unclear	Intermediate	Normal to slightly decreased
IV	Inhomogeneous, gray to black	Lost	Intermediate to hypointense	Normal to moderately decreased
V	Inhomogeneous, black	Lost	Hypointense	Collapsed disc space

* Reference 10.

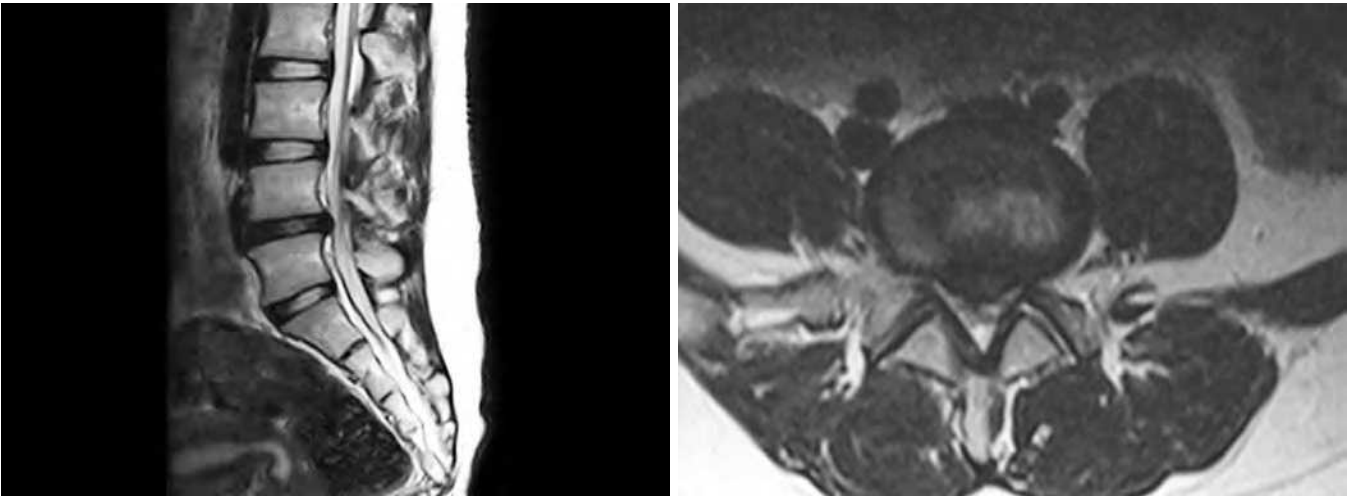


Fig. 101.1: Magnetic resonance imaging of 16-year-old girl indicated L4/5 disc herniation.

volume of abscess, and direction of abscess interfering, and also differentiate infection and tumor.¹⁴ Superiority of MR for assessment of neurological structure has made it the first choice to identify congenital neural tube developmental dysfunction. Many investigators recommend MR as the mandatory preoperative examination of congenital spine deformity, which has 20–30% rates of intracanal anomalous conditions.

SPECIAL CLINICAL ENTITIES

Lumbar Disc Herniation

Lumbar disc herniation is not a common cause of lower back pain among children and adolescents. The onset of symptoms in a child is less acute and severe, while in an adolescent it is present with an acute process. The real incidence of pediatric disc herniation in lumbar disc excisions of all ages seems difficult to establish and is reported

to range from 0.4% to 3.8%.^{15–17} Prevalence in adolescent athletes has been reported to increase.¹⁸ One of the most likely factors accounting for the early onset of lumbar disc herniation is its association with vertebral deformities, such as scoliosis, transitional defects, schisis, and canal narrowing. In these cases, the reported incidence ranges from 30% to 70%,^{19,20} compared with 15% cases in a healthy population.²¹ These alterations can cause an anomalous biomechanical stress for disk. Additionally, many authors hypothesize familial predisposition to be another etiologic factor for disc herniation and some evidence was found.²²

The diagnosis of lumbar disc herniation still depends on the physical examination and image tools. The SLR test and other nerve root localization signs are the best evidence for identified diagnosis of lumbar disc herniation. Then, definitive diagnoses require MR or CT confirmation (Fig. 101.1).

Conservative treatments of disc herniation cover bed rest, activity restriction, and anti-inflammatory medications. Some authors reported that bracing has an accepted results.²³ Other investigators suggested high failure rate of conservative treatment. Surgery is recommended for failure of conservative treatment, and decompressive laminectomy and discectomy are the standard procedures. Mayer reported the results of using percutaneous endoscopic discectomy for pediatric and juvenile lumbar disc herniations. During the 1–5-year follow-up, all four cases acquired good-to-excellent outcomes without any complications.²⁴

Spondylolysis and Spondylolisthesis

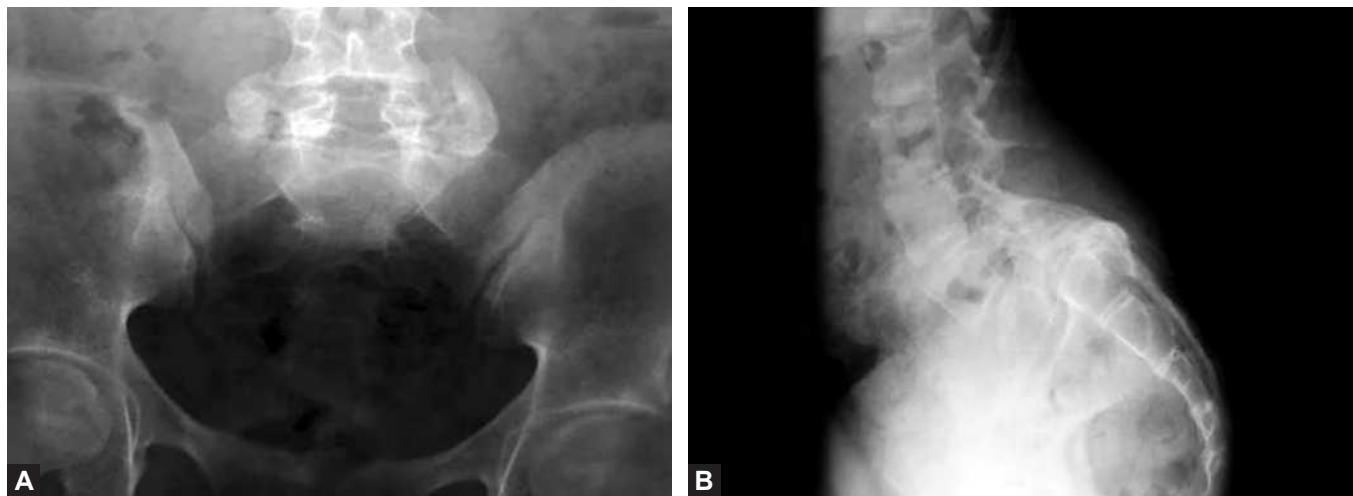
Spondylolysis and spondylolisthesis have been widely accepted as the most underlying causes of low back pain among children and adolescents.²⁵ Spondylolysis is a defect in the neural arch, most commonly the pars interarticularis. Spondylolisthesis is an anterior translation of one vertebra on another or on the sacrum. The reported incidence is 6% in general population, but varied in different ethnic groups or in people who engage in different sports. Spondylolysis and spondylolisthesis have been referred to as congenital anomalies of the spine, but there is no supporting embryological or anatomical evidence for this assumption.

Spondylolysis occurs in children rarely before 5 years, more commonly in 7–8 years, and increase until 20 years.^{26,27} Most authors believed that stress and micro-trauma are important factors in the etiology. Athletic participation has been reported an increased incidence of spondylolysis and spondylolisthesis. Jackson noted that the incidence of spondylolysis in female athletes was 11% (four times higher than normal).²⁸ In adolescent athletes, spondylolysis is the cause of pain in an estimated 47% cases, compared to only 5% of pain in adult athletes. Football linemen and gymnasts have a higher likelihood of spondylolysis.²⁹ Therefore, a high-level sport-related low back pain should be suspicious of spondylolysis and spondylolisthesis.

The comprehensive classification of spondylolysis and spondylolisthesis was proposed by Wiltse.³⁰ This discussion is limited to isthmic (type II) spondylolysis and spondylolisthesis, the two types that commonly occur in children and adolescents. Some anatomical studies have suggested that shear stresses are more on the pars interarticularis when the lumbar spine is extended.³¹ In young people, the pars interarticularis is thin and neural arch

has not reached its maximum strength.³² A fatigue fracture of the pars interarticularis can occur at physiological loads during cyclic flexion–extension motion of the lumbar spine. The pain associated with an acute pars stress fracture is believed to be related to the biology of fracture site. Nordström noted that the pain of spondylolysis and spondylolisthesis might derive from the spondylolytic defect itself, probably from stretching of the local neural elements rather than from their sensitization/stimulation by local inflammatory mediators.³³ Low back pain, postural deformity, or abnormal gait resulting from tightness of the hamstrings would be the most common complaints of spondylolysis and spondylolisthesis. Symptoms are usually initiated or aggravated by strenuous activity, particularly the repetitive flexion extension of the spine. Physical examination may find tenderness in the lumbosacral region or restriction in truncal motion. Tight hamstrings may be found in patients with spondylolysis or any grade of spondylolisthesis, and this is seldom accompanied by neurological signs.³⁴ The tightness may be so extreme that the child cannot bend forward at the hips or during the straight leg-raising test. In lower-grade slip, tight hamstrings may be the only positive findings of physical examinations. Conversely, it would be common in high-grade slips, combined with mild scoliosis, flattening of buttocks, rotated pelvic, and compensated knee flexion for stand (Figs. 101.2A and B).

Lateral X-ray films are enough to demonstrate the grade of spondylolisthesis. If pars defect is large enough, it can be viewed in all radiographic examinations. Especially, if it is unilateral, as in 20–25% of patients, or if it is not accompanied by spondylolisthesis, it can be a very subtle finding that can be identified only by special radiographic techniques, such as oblique view, or flexion or extension lateral films.³⁵ Oblique radiographs of the lumbar spine are often necessary to view this area in relief, typically, a break in the pars interarticularis called “Scottie dog” sign. Libson noted that the diagnosis will be missed in 20% of young symptomatic patients if oblique radiographs are not made.³⁶ In fact, pars lytic lesion within the neural arch is not always present on plain radiographs. In the event of negative plain radiographs in a patient with back pain, bone scan with SPECT is a useful adjunct, especially for the prespondylolytic stress lesion.^{37,38} This will show an increased uptake at areas of the bone with increased turnover, so it will be positive with a stress reaction to stress fracture to complete fracture. If the SPECT is positive, CT



Figs. 101.2A and B: (A) Posteroanterior and (B) lateral standing radiographs of a 13-year-old girl with L5 symptomatic high-grade spondylolisthesis.

of the affected area is indicated for the morphology of the pars and the rest of the neural arch. A standard CT can also help with prognostication. If a pars defect is sclerotic, then it is most certainly a chronic defect and is less likely to heal with bridging bone. Udeshi and Reeves showed that using 3 mm on T1-weighted images and 4 mm on T2-weighted images they are able to adequately assess 98.2% of pars on T1-weighted images and 93% on T2-weighted images.³⁹

The treatment choice for spondylolysis and spondylolisthesis is based on the acuteness of pars defect and degree of spondylolisthesis, including observation, bed rest, restrict activity, exercise, bracing, and or surgery. Bracing is a wide-accepted therapeutic option. The acute injuries are treated with 12 weeks of bracing and the chronic injuries are treated until they are pain free. Although spondylolysis of long duration is not likely to heal, a clinical response to simple nonoperative measures can still be expected.⁴⁰ Micheli achieved 90% good-to-excellent results with antilordotic bracing in acute lesion.⁴¹ Iwamoto showed that in chronic lesion 88% of patients were able to return to their sport with rest and antilordotic bracing, at an average time of 5.4 months.⁴² Concerning to grade of spondylolisthesis, high-grade slips are always associated with intractable back or leg pain, progressive neurological symptoms, then surgery is generally recommended.⁴³ Direct repair should preserve the motion segment, but this is still a theoretical benefit without good evidence of patient's improvement when compared to fusion. Spine fusion is the most common choice for high-grade spondylolisthesis. Surgery strategy

Table 101.3: Risk factors of slip progress in low-grade spondylolisthesis.

<i>Clinical</i>	<i>Radiographic</i>
Adolescent growth	Dysplastic slip
Female	Domed sacrum
History of back pain	Slip > 40–50%
Increased motion in dynamic X-ray	

may cover fusion with or without reduction, decompression or not, fixation or not. A new grade proposed by Spinal Deformity Study Group, based on slip grade and spinopelvic alignment, is recommended in the evaluation and treatment of spondylolisthesis.⁴⁴ Severe index reported by Lamartina is helpful in identifying low-dysplastic developmental spondylolisthesis from high-dysplastic developmental spondylolisthesis (HDDS) and allowing earlier surgical stabilization to prevent slip progression.⁴⁵

The natural history of low-grade spondylolisthesis is considered benign, but the risk factor of slip progress should be assessed. Related risk factors are listed in Table 101.3.

Scheuermann's Kyphosis

In 1920, Scheuermann⁴⁶ first published a paper on thoracic or thoracolumbar spine kyphosis in adolescents. The pathological process of Scheuermann's kyphosis is characterized by vertebral wedging, endplate irregularity, and narrowing of the disc space with or without disc herniation (Fig. 101.3). The common main complaint of this condition

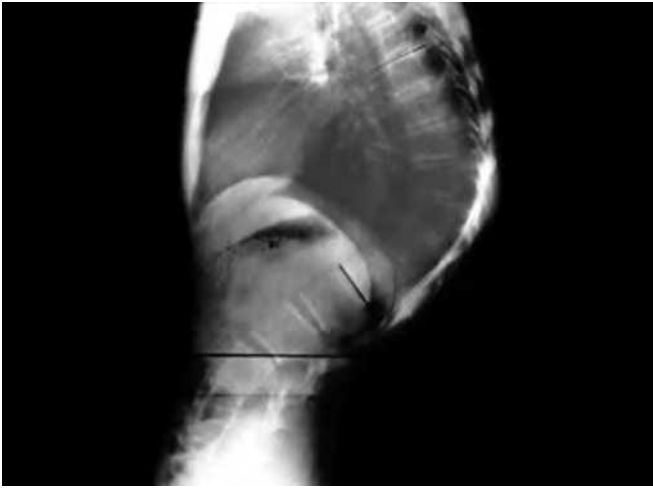


Fig. 101.3: X-ray of a 17-year-old boy showed kyphosis of thoracolumbar segment caused by multilevel vertebral wedging.

is not lower back pain but deformity or poor posture of parent's concern. Back pain is present in 20–30% of the cases. Its incidence ranges from 1% to 8% of the general population, although its true incidence is probably understated for attributed to poor posture.^{47,48} The main differentiated points of postural kyphosis from Scheuermann's kyphosis include the presence of a uniformly rounded kyphosis that is nonstructural, the absence of wedged vertebral bodies (VBs), and disc degeneration. Radiographically, the Scheuermann's kyphosis is the structural kyphosis accentuated on flexion films and does not resolve on extension films.

The etiology of Scheuermann's disease remains unknown. An increased familial incidence of Scheuermann's kyphosis is noted by several investigators.^{49,50} Damborg et al.⁵⁰ reviewed 35,000 twins to establish a cohort of symptomatic twins with Scheuermann's kyphosis recorded in the Danish twin registry. They found that the pairwise concordance for monozygotic twins was 0.19 compared with 0.07 for dizygotic twins. The probandwise concordance was 0.31 for monozygotic twins and 0.07 for dizygotic twins. Heritability was 74%. These findings indicate a major genetic contribution to the etiology of Scheuermann's kyphosis.

Histopathologically, Scheuermann indicated avascular necrosis of ring apophysis caused the wedging of VB although other investigated noted ring apophysis does not contribute to vertebral growth. Recently, Scoles noted disorganized enchondral ossification similar to Blount's disease, a reduction in collagen, and an increase in

mucopolysaccharides in the endplate, is noted in patients with Scheuermann's kyphosis.⁵¹ Mechanical factor is also considered for the fact that kyphosis may appear before VB wedging. Other investigators reported thickening of the anterior longitudinal ligament and partial reversal of the vertebral wedging after brace treatment, implying the mechanical theories of pathogenesis.^{52,53} Paaajaen showed degeneration of the disks on magnetic resonance imaging (MRI) in half of the young patients with Scheuermann's kyphosis as opposed to 10% of asymptomatic controls.⁵⁴ It is probable that multifactors contribute to the pathogenesis of Scheuermann's kyphosis, some genetic and some environmental; further investigation will be needed before any definite conclusions can be reached.

The onset of Scheuermann's diseases usually appears just before puberty, after ossification of the ring apophysis, as a structural kyphotic deformity of the thoracic or thoracolumbar spine. Two different curve patterns have been described in Scheuermann's kyphosis. The thoracic pattern is the most common and usually involves more than one level associated with a nonstructural hyperlordosis of the lumbar and cervical spines. The thoracolumbar pattern is uncommon and affects usually a single level with less severe vertebral wedging, but it is thought to be the most likely to progress in adulthood. Although pain is not a common medical seeking reason, it does interfere daily lives. Murray noted that 38% of the patients with Scheuermann's kyphosis had significant interference with activities of daily living because of pain compared with 21% of controls.⁵⁵ A mild scoliosis can also be found in ~30% patients. The thoracolumbar or lumbar curve is often more painful than the thoracic curve.⁵⁶

Naturally history of Scheuermann's kyphosis is lack of literature, so there are questions that still need to be answered in order to improve the recommendations for treatment. Untreated case series with progressing deformity even with neurological complications have been reported in literatures.⁵⁷⁻⁵⁹ Bracing has widely been regarded as efficacious in the treatment of kyphosis secondary to Scheuermann's kyphosis in skeletally immature patients, which is often a long-time therapeutic program till the skeletal maturing is reached. Montgomery and Erwin reviewed 39 patients with Scheuermann's kyphosis who were treated with a modified Milwaukee brace for an average of 18 months. The kyphosis before treatment is averaged 62° and after the completion of brace treatment is averaged 41°. Follow-up of >18 months after completion

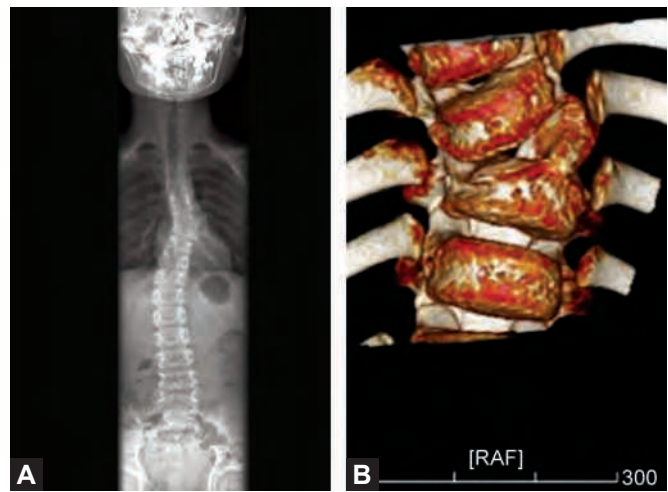
of brace wear showed an average of 15° loss of correction, resulting in an average overall correction of 6°. They found that brace treatment was successful in improving kyphosis >75° in several cases.⁶⁰ Flexible deformities seemed to predict successful brace treatment. Adolescent patients can always be successfully treated by bracing. In a few patients with progressive deformity accompanied by pain that does not respond to bracing, spine arthrodesis with instrumentation is mandatory.⁶¹

Scoliosis

Usually, idiopathic scoliosis is a pain silence process in terms of lower back pain. Typical idiopathic scoliosis curves are right thoracic and left lumbar curves. A child with a pain complaint, left thoracic curve, and neurological dysfunction should be assessed for other causes of scoliosis.

There are many pathological processes that can present with scoliosis. Osteoid osteoma and osteoblastoma are the most common painful scoliosis. Sciatic scoliosis can also be found in the childhood lumbar disc herniation. Spine infection condition can present with a mild scoliosis. But under these painful scoliosis conditions, vertebral rotation and severity of scoliosis are often mild, compared with typical idiopathic scoliosis. Spontaneous curve correction can occur while the etiology of pain has been removed. Some investigators noted that although a painful scoliosis exists for long time, a compensated scoliosis would be turned into a structure scoliosis.⁶²

Congenital scoliosis and intraspinal canal anomaly-related scoliosis often present with a left thoracic curve (Figs. 101.4A and B). Improved imaging of the central nervous system with MRI has led to the diagnosis of subclinical hydrosyringomyelia (and other lesions) associated with scoliosis.^{63,64} The incidence of intraspinal anomalies of congenital scoliosis is 18–38%.^{65–67} Detailed examination and figured out atypical scoliosis radiographic curve helped the surgeon to distinguish the exact etiological classification of scoliosis. Table 101.4 listed the common indications for MR examination. Other system anomalies are also not rare in congenital scoliosis; the incidence of cardiac as well as genitourinary involvement is 10–26%⁶⁸ and 13–33%, respectively.^{69,70} Pulmonary involvement is also commonly seen in children with congenital scoliosis. The deformity alters normal pulmonary function and leads to the development of thoracic insufficiency syndrome and later the development of restrictive lung



Figs. 101.4A and B: (A) Standing AP X-ray indicated congenital scoliosis caused by T7 hemivertebra. (B) Three-dimensional reconstruction CT showed structures of T7 hemivertebra. (AP: Anteroposterior; CT: Computed tomography).

disease. Campbell recommends a detailed study of both radiographic and clinical parameters to check for lung function.⁷¹ Plain X-ray features of nonidiopathic scoliosis include curve type, widening of pedicle distance, narrow disc space, sagittal anomaly alignment, and spinal bifida occulta.

Discitis

Clinical features of discitis in childhood and early adolescence are perplexing. The exact etiology is controversial; some consider it as an infective process affecting the disc or endplates,^{72,73} while others consider it as an inflammatory condition.^{74,75} Among the pyogenic infections, terms “discitis” and “osteomyelitis” are different manifestations of the same pathological process.

The average age for diagnosis of discitis in children is ~2–8 years. The incidence of involvement of the lumbar or lumbar-sacral region represents the majority of cases (75% of patients).⁷⁶ Diagnosis of childhood discitis is difficult because the symptoms are not very specific and children face difficulty in communicating. Commonly, there are abrupt symptoms, such as abdominal pain, fever, and difficulty walking, and other decreased activity findings.^{77,78} The laboratory variables to be determined include leukocyte count, CRP, and ESR. Usually, in patients with acute disease, significant increased values of the inflammatory tests, CRP, and ESR can be observed, while in patients with chronic infections, such as tuberculosis, these tests can show normal or only slightly elevated results.⁷⁹ Blood cultures, usually

Table 101.4: Indications for magnetic resonance imaging.

<i>Pain</i>	<i>Neurological findings</i>	<i>Atypical curve pattern</i>
Back	Clonus	Left thoracic
Neck	Abnormal abdominal reflexes	Short segment (4 to 6 levels)
Radicular	Weakness	Decreased vertebral rotation
Headache	Urinary dysfunction (urinary tract infection)	Absence of thoracic apical segment lordosis
	Hyperreflexia	Rapid progression
	Asymmetric deep tendon reflexes	
	Paresthesias	
	Diminished rectal tone	
	Cavus foot deformity	
	Skin lesions	

obtained from two or three samples, are positive in 50% of the cases of unspecified discitis, and are an important guide to antibiotic therapy. In patients who have already begun taking antibiotics, the rate of identification of the pathogen decreases to around 15%. In these cases, the antibiotic therapy should be suspended for 72 hours before collecting new blood cultures.^{80,81} Biopsy of the VB and/or disc space should be considered when no organism can be identified by less invasive techniques, *Staphylococcus aureus* being the most common identified organism.

Clinical presentation of discitis can be very confused, often with unspecific symptoms, making its diagnosis difficult.⁸² The pain can distribute in hip, leg, or abdomen. The prevalence of back pain is reported to occur more commonly in children of ≥ 3 years. For the wide presentation of symptoms, delay diagnosis often arises; then a number of examinations are performed for final exact diagnosis.

Radiographs have very low sensitivity and specificity in the early stages of discitis. The earliest radiographic sign is the loss of definition and irregularity of the vertebral endplate, which can occur within 2–8 weeks of the onset of symptoms. Disc space can be narrow after 2–6 weeks. Previously, radionuclide bone scan can be performed to obtain early diagnosis of discitis. Recently, MRI has been the most useful imaging method for the investigation of discitis of the spine, particularly in the early stages. Magnetic resonance imaging has high sensitivity (96%) and high specificity (94%) for diagnosis spine infection.⁸³

The treatments of discitis in children depend largely on the exact diagnosis and conservative treatment. The principles of conservative treatment include treatment with specific antibiotics, spinal immobilization. In most cases, conservative treatment is usually sufficient, most of the patients' symptoms improving satisfactorily and

without sequelae. When laboratory tests are negative and no clinical and laboratory responses to the therapy are observed, percutaneous biopsy of the affected disc is indicated. Given the lack of specificity and poor biopsy results, the therapeutic test is indicated according to the clinical, the laboratory, and the imaging history of the cases. Some studies advocate that when discitis is suspected in children, antibiotic treatment should be empirical, based on the assessment of the probable organism and the patient's risk factors.^{84,85} Surgical irrigation and debridement is indicated while clinical infective symptoms and laboratory examination recur.

BONE TUMORS

Benign Tumors

Osteoid Osteomas and Osteoblastoma

Osteoid osteomas and osteoblastoma are the most common bone producing tumors of spine and frequently localized in posterior elements of the vertebra. These benign lesions usually occur predominantly in patients of < 20 years of age and osteoblastoma may have an older onset age distribution.^{86,87} The most common presenting symptom is pain, which can be relieved by aspirin characteristically. The pain of osteoblastoma is not as severe at night, nor is relieved by aspirin, as is the pain of osteoid osteomas. Both of these tumor types tend to occur in the thoracic and lumbar spines. For osteoid osteomas, it is small and not easy to find on routine X-ray, bone scan, CT and/or MRI can be useful in diagnosis and localization.^{88,89} Osteoblastoma and osteoid osteoma are histologically similar in many regards. The basic microscopic pattern in osteoblastoma and osteoid osteoma is bone-forming tumor containing numerous osteoblasts producing osteoid and woven bone.⁹⁰

Osteoid osteoma is predominantly marked in males, with a number of studies reporting a male-to-female ratio of 2:1 to 4:1.⁹¹ It often arises in the posterior arch region and has been widely accepted as the most common cause of pain scoliosis in adolescents. Scoliosis with less vertebral rotation and nidus located in the center of concave side is the main radiographic feature that differentiated with idiopathic scoliosis. The recommended treatment for osteoid osteoma causing disabling pain and spinal deformity is excision. The most important determinant for successful removal of the tumor is its exact localization, which can be aided with tetracycline labeling, CT,⁹² or MRI. Recently percutaneous radiofrequency thermal ablation and laser photocoagulation have been promoted as a minimally invasive treatment for osteoid osteoma located in the spine.⁹³⁻⁹⁵ However, lack of histological verification of the specimens, risks of thermal damage to the neural structures, and incomplete resection causing recurrence are the main shortcomings of these minimally invasive treatments.

Osteoblastomas are usually >2 cm and 40% locating in the spine. Compared with osteoid osteoma, osteoblastoma has more aggressive characteristics and often forms extra skeletal bone in the soft tissue. The pain is not responsive to aspirin and with less painful scoliosis. Because of its more aggressive features, spine osteoblastomas often present with symptoms related to spinal cord or root interfering. The first choice of osteoblastoma is the en bloc excision and decompression.

Aneurysmal Bone Cyst

Aneurysmal bone cysts (ABCs) are benign, highly vascular osseous lesions characterized by cystic, blood-filled spaces surrounded by thin perimeters of expanded bones. Aneurysmal bone cysts predominantly arose in children, with 60% of patients being <20 years. There is a slight preponderance for women over men.⁹⁶ Primary ABCs represent 1.4% of primary bone tumors and 15% of all primary spine tumors.⁹⁷ Almost 70% of cysts are seen in the thoracolumbar region, and <25% are seen within the cervical spine⁹⁸ and can affect more than one vertebral level. Of aneurysmal bone cysts, 60% occur in the pedicles, laminae, and spinous processes. Most patients present with symptoms of ill-defined dull pain, stiffness, swelling, and 10% patients have scoliosis or kyphosis. Neurological dysfunction is not rare for large cysts causing vertebral collapse.⁹⁹

Computed tomography typically reveals a characteristic soap bubble appearance, which represents a balloon-

ing, multilocular lytic lesion. Pathological fracture or partial VB collapse is not rare. Magnetic resonance imaging is useful in assessment of soft-tissue involvement and compromises neural elements.^{100,101} Multilocular cysts with fluid-fluid interfaces on MR T2-weighted images are highly suggestive of ABCs.¹⁰² The mainstay of treatment is surgery and most patients are cured with one or more operations. A small subset of patients with incomplete resectable, aggressive, and/or recurrent ABCs may be cured with low-dose radiotherapy (RT).

Osteochondroma

Osteochondroma is most asymptomatic in childhood. In most cases, it is presented with chronic-growth mass and secondary neurological compression symptoms. Surgical excision is the symptomatic osteochondroma choice.

Malignant Lesions

Primary malignant tumor seldom involves the spine in pediatric population. Ewing's sarcoma and osteogenic sarcoma are most common in this age population. Back pain and cord or root compressive symptoms are the common complaints of these patients.

Unfortunately, Ewing's sarcoma (ES) and osteogenic sarcoma (OS) are associated with aggressive local and metastatic spreads if left untreated or if residual disease remains after surgery. It has been widely accepted that chemotherapy or surgery alone effect cure in a few patients,^{103,104} patients are usually treated first with radiation and concomitant chemotherapy followed by surgical resection in spine.^{105,106} Some experts concluded that appropriate oncological and surgical staging is required to determine the feasibility of en bloc resection of ES and osteogenic sarcoma of the spine with acceptable margins.¹⁰⁷ The morbidity and mortality of obtaining wide and/or marginal margins in the spine are significant and therefore these operations should only be performed by experienced multidisciplinary teams.¹⁰⁸

Neuroblastoma is the most spine metastasis in children and adolescents. The prognosis is highly variable, with outcome related to age, stage, and molecular pathology. Neuroblastoma may behave in an almost benign way, with spontaneous regression in some infants, but the majority of older patients have high-risk disease, which is usually fatal. High-risk disease requires multimodality therapy including chemotherapy, surgery, and radiotherapy as well as biological and immunological treatments for optimal outcomes.

PSYCHOSOMATIC PAIN

Psychosomatic pain is a diagnosis after exclusion of any suspicious diagnosis. In some patients, symptoms seem to exceed physical examination and who might be subject to stresses from home, school, or other social factors. It has been reported that smoking or recent psychosocial stress in the family might affect the incidence of LBP in children.¹⁰⁹ Jackson et al. recommended some questions to evaluate the response of children to LBP including the following questions: "If you had to assign a color to this pain, what would it be? If you had to picture your pain as an animal, what would it be? Why? What do you do to help the pain? What can we do to help your pain?" Counseling with pediatric psychiatrists might be necessary. In case of finding any positive psychosocial history, proper intervention should be done.

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Congenital Scoliosis

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Snapshot

- » Evaluation
- » Surgical Options
- » Preoperative Planning
- » Hemivertebra Resection
- » Spinal Growth following Transpedicular Instrumentation

INTRODUCTION

Malformations of the spine represent a wide variety of conditions that may result in various deformities. Disturbance of the development occurs in the early embryologic period. The formation of the somites, the precursors of the vertebral bodies, begins at about 3–5 weeks of gestation. They begin to segment at 6–8 weeks. Normal somitogenesis may be affected by genetic or environmental factors.¹

The specific abnormality affects the further growth of the spine. Asymmetric or decreased growth may result in scoliosis, kyphoscoliosis, or a short trunk. Depending on the type of malformation Winter et al. divided the abnormalities into failure of formation, failure of segmentation, and complex (mixed) deformities.^{2,3} Figure would be ideal defects of formation include unilateral or posterior hemivertebrae. They may be fully segmented with two adjacent disc spaces, semi-segmented, or nonsegmented. Except in cases of some incarcerated vertebrae, the hemivertebra has growth potential similar to a normal vertebra, thus creating a wedge-shaped deformity that progresses during further spinal growth. Segmentation defects include bar-formations spanning one or more segments that may be located lateral, anterior, or posterior. The bar-formations usually result in a delay or cessation of growth. Asymmetric bars lead to asymmetric growth with progressive scoliosis, kyphosis, or lordosis. Mixed

deformities are frequent, often combined with abnormalities of the rib cage. Rib deformities, especially rib synostosis, may increase the scoliotic deformity of the thoracic spine.

The natural history of congenital scoliosis is well described.^{4,5} The rate of progression and the ultimate severity of the curve depend on the type of anomaly as well as the site at which it occurs. Acceleration of the progression of the scoliosis may be expected during the growth spurts. The primarily unaffected vertebrae, adjacent to the original deformity, are subject to asymmetric loads. With growth the asymmetric loads lead to a wedge-shaped deformity of these vertebrae. The rigidity of the main curve increases. Secondary curves develop to promote trunk equilibration. These curves are flexible in the beginning, but become structural with time.

EVALUATION

Clinical and Radiological

Therapeutic Considerations

The asymmetric growth based on formation or segmentation defects cannot be influenced by braces or casts. These nonsurgical treatment options induce and fix compensating curves.

Role of Observation

The only effective treatment is surgical. The indication for surgery depends on the degree of scoliosis at the time of diagnosis and the expected further progression. According to McMaster, the worst prognosis is a hemivertebra with a contralateral bar, followed by two unilateral hemivertebrae, and fully-segmented single hemivertebra.⁴ In these cases, surgery is usually required. If there is any doubt about further progression, especially in semi-segmented or incarcerated types or hemivertebrae in the upper thoracic spine, frequent radiographic follow-up is imperative. In case of significant progression surgical intervention is recommended.

The goal of treatment of congenital scoliosis is to achieve a straight spine with a physiological sagittal profile and limited growth deficit. To meet this goal early diagnosis and early surgical intervention in young children is indispensable. Surgery should be performed before the vertebrae adjacent to the hemivertebra develop an asymmetric shape, and before secondary curves become structural. In addition, the spine in very young children is highly flexible; deformity correction following resection of the hemivertebra requires little force. The risk of neurological impairment is minimal. With early and complete correction of the local deformity the development of secondary changes can be avoided. Thus, primarily healthy segments are allowed to grow physiologically. In cases of delayed treatment in older children or adults secondary structural curves need to be addressed resulting in longer fusions. For these reasons, the most favorable age for surgery is 1–5 years.

SURGICAL OPTIONS

Many different surgical procedures for treatment of congenital scoliosis have been described. Several procedures aim at preventing further progression of the deformity. Posterior fusion was the standard treatment over several decades. It may be effective if performed early before severe curves develop.^{2,3,6,7} A bilateral fusion is performed either with or without instrumentation. Most common problem of this technique is failure due to nonunion or progression of the deformity despite a solid posterior fusion. Convex anteroposterior hemiepiphysiodesis/arthrodesis is reported to achieve stabilization or even a certain correction in young children with mild curves.^{8,9} The results, however, are unpredictable and depend on the concave growth potential.

Corrective surgical techniques should aim at a maximum correction with minimum impairment of spinal growth. A precise analysis of the type of deformity and preoperative planning is imperative. Short angular deformities caused by a single hemivertebra or a monosegmental segmentation defect should be corrected completely with a short fusion. Loss of growth by a mono- or bisegmental fusion is minimal. Complex deformities, e.g. with multiple hemivertebrae, multisegmental bar formations, and accompanying rib synostosis require a more sophisticated therapy. Depending on the length of the involved spinal segment, the expected remaining growth, and possible rib cage abnormalities, nonfusion techniques, if necessary in combination with correction and short fusion of the apex of the deformity, may be applied.

PREOPERATIVE PLANNING

Preoperative radiographic examination includes X-rays of the whole spine and the region of the deformity in a standing position. If necessary, bending films are obtained to assess flexibility especially of the secondary curves. Computed tomographic (CT) scans with three-dimensional reconstructions are indispensable to evaluate the shape and location of the hemivertebra and the adjacent vertebrae, and to provide information on bar formations or ribs synostoses. The size and diameter of the pedicles are measured to select proper size of the screws. Three-dimensional reconstructions are helpful for surgical planning especially in mismatched abnormalities of the anterior and posterior structures.

Congenital malformations of the spine are frequently accompanied by spinal dysraphism and genitourinary and cardiac problems.^{10,11} Magnetic resonance imaging (MRI) of the spinal cord is obligatory to evaluate for malformations that may require neurosurgical intervention. Ultrasound screening should be performed to exclude genitourinary and cardiac changes. Briefly more on associated congenital malformations with the incidences. Staging of neurosurgical procedures in congenital scoliosis or whether it can be done in one stage. Controversies regarding whether to operate on all intraspinal abnormalities should be addressed.

HEMIVERTEBRA RESECTION

In the case of hemivertebrae resulting in congenital scoliosis the resection of the hemivertebra resection offers an efficient therapy. In the great majority of cases at the thoracolumbar spine a single posterior approach is

sufficient for a complete resection of the hemivertebra with fusion of the adjacent segments. Only at the cervical spine a combined anterior and posterior procedure is required due to the vertebral arteries. At the lumbosacral junction, an additional anterior approach may facilitate complete resection of the body of the hemivertebra.

Hemivertebra resection was first described by Royle in 1928.¹² In the beginning poor results and a high rate of complications such as pseudarthrosis, kyphosis, and neurological deficits were discouraging. In 1979, Leatherman reported on improved results in a larger series of hemivertebra resection in a two-stage procedure.¹³ Further reports on resection of hemivertebrae by a combined anterior and posterior approach followed. Closing of the wedge after resection was achieved by casts and braces that were applied for about 6 months,¹⁴⁻¹⁷ by sutures or wires,^{18,19} or by a posterior hook-rod instrumentation.^{14,16,20-25} More recently reports on hemivertebra resection by a single posterior approach were published.²⁶⁻⁴⁰ Pedicle screws have been demonstrated to be safe and efficacious even in very young children.⁴¹

Posterior Hemivertebra Resection: Surgical Technique

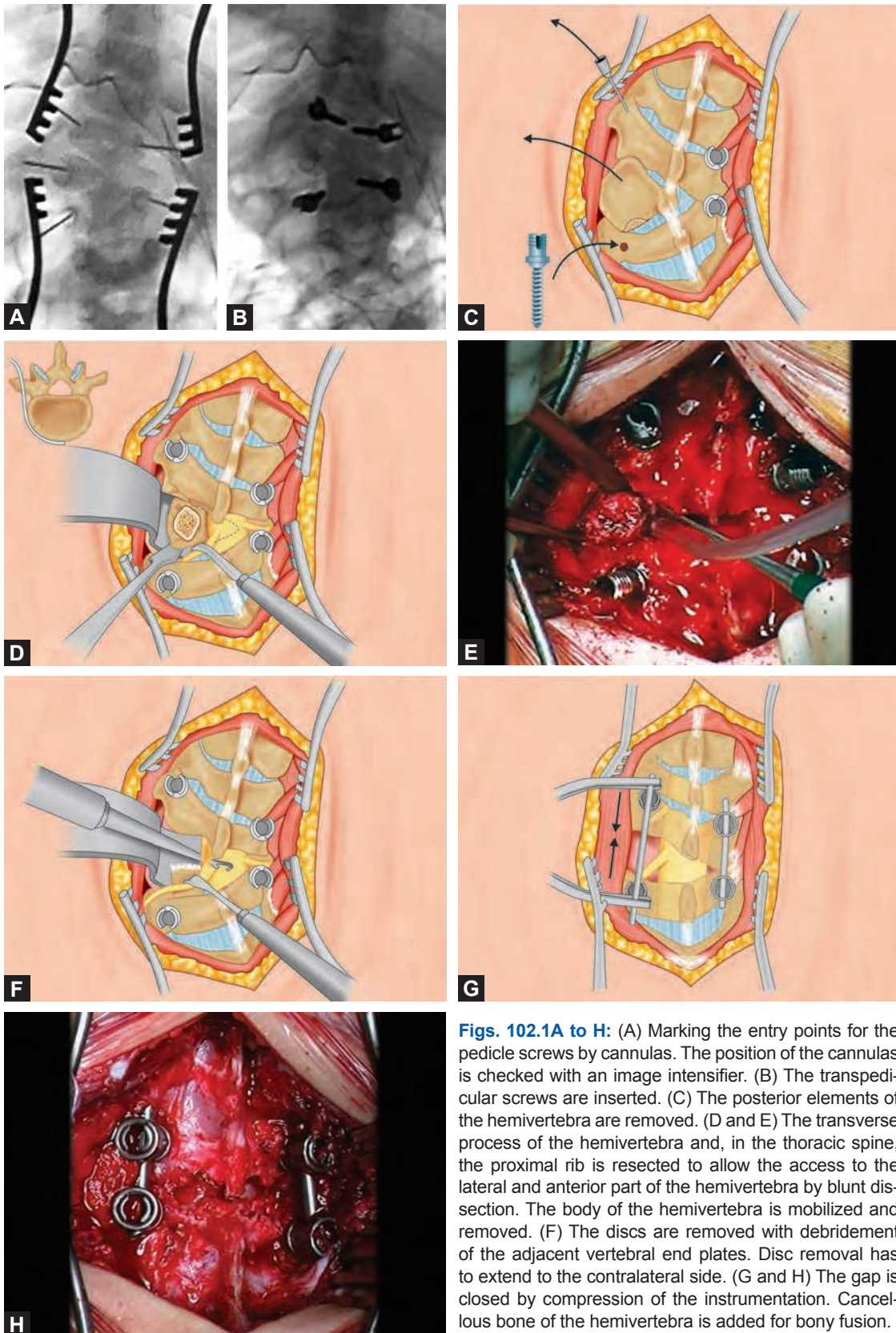
The following technique of hemivertebra resection was introduced by Jürgen Harms in 1991.²⁸ The technique is especially suitable in young patients with mobile segments around the hemivertebra. It offers several advantages as follows:

- The complete resection of the hemivertebra is performed by means of a less invasive single posterior approach.
- An excellent correction in both the frontal and the sagittal planes is achieved.
- The transpedicular instrumentation ensures a high stability and allows for a short fusion.
- Early mobilization is possible that is especially important in young children.
- The spinal cord is visible during the correction maneuver that minimizes neurologic risk.
- The technique is applicable in very young children as early as 1 year of age.

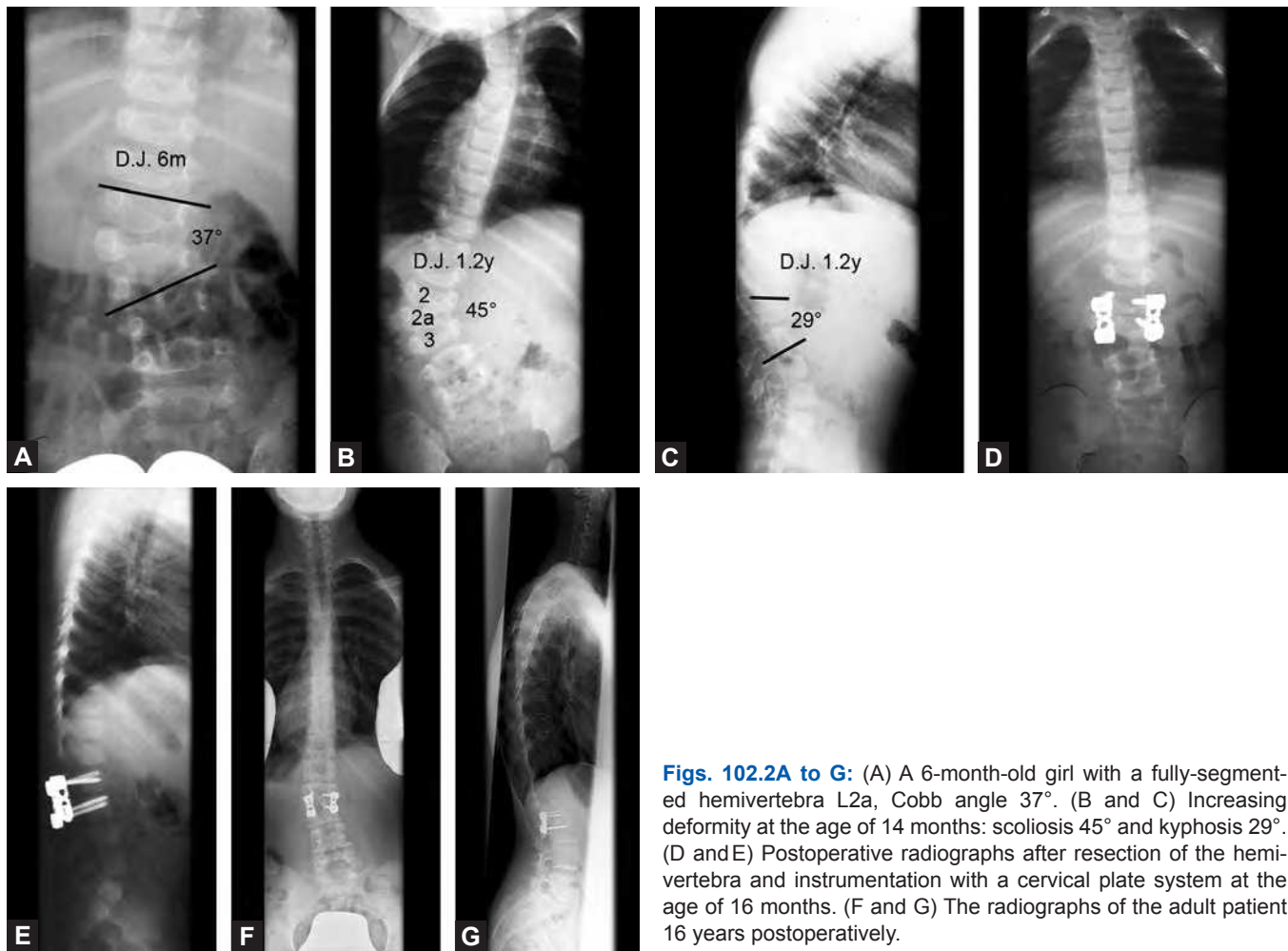
Patients are placed in prone position. The posterior elements of the spine are carefully exposed at the affected levels, including the lamina, the transverse processes, the facet joints, and, in the thoracic spine, the rib head on the convex side. This exposure should meticulously maintain the periosteum at the bony structures except at the area,

where fusion is planned. The entry points for the planned pedicle screws are marked by cannulas and their position checked by an image intensifier in an anteroposterior view (Fig. 102.1A). This identification of the pedicles is particularly important in cases with mismatched abnormalities of the anterior and posterior structures. The landmark for the entry point for the pedicle screw in the lumbar region is the base of the transverse process at the lateral border of the superior articular facet. In the thoracic region, the entry point is at the superior margin of the transverse process slightly lateral to the lower lateral edge of the articular facet. After verifying the correct position of the cannulas the bone at the pedicle entry points is opened with a sharp awl or small burr. A 1.5- or 2.0-mm drill is incrementally advanced through the pedicle into the vertebral body. The drill-holes are marked with Kirschner-wires. Their correct position is checked with an image intensifier. After tapping, the screws are inserted (Fig. 102.1B). Screw diameter depends on the size of the pedicle. In children <5 years of age 3-mm screws are usually appropriate.

The posterior elements of the hemivertebra are removed. Resection includes the lamina, the facet joints, the transverse process, and the posterior part of the pedicle (Fig. 102.1C). The spinal cord and the nerve roots above and below the pedicle of the hemivertebra are identified. In the thoracic spine, the rib head and the proximal part of the extra rib at the convex side are resected as well. After resection of the transverse process and the rib head, the lateral and anterior part of the hemivertebra at the convex side can be exposed by blunt dissection. This exposure is retroperitoneal in the lumbar spine and extrapleural in the thoracic spine. A blunt spatula is inserted to protect the anterior lying vessels. The remnants of the pedicle are removed and the posterior aspect of the vertebral body of the hemivertebra is exposed. This is facilitated by the fact that the hemivertebra lies far laterally on the convex side, while the spinal cord is usually shifted to the concave side. The discs adjacent to the hemivertebra are incised and the body of the hemivertebra is mobilized and removed (Figs. 102.1D and E). The rest of the disc material at the upper and lower vertebra is removed completely with debridement of the vertebral end plates to bleeding bone. This meticulous disc removal has to extend to the contralateral side (Fig. 102.1F). In cases of pronounced kyphosis, an anterior column support, using a titanium mesh cage, may be added to create a fulcrum to achieve lordosis. The instrumentation is completed and compression is applied on the convex side until the gap, which remains after the



Figs. 102.1A to H: (A) Marking the entry points for the pedicle screws by cannulas. The position of the cannulas is checked with an image intensifier. (B) The transpedicular screws are inserted. (C) The posterior elements of the hemivertebra are removed. (D and E) The transverse process of the hemivertebra and, in the thoracic spine, the proximal rib is resected to allow the access to the lateral and anterior part of the hemivertebra by blunt dissection. The body of the hemivertebra is mobilized and removed. (F) The discs are removed with debridement of the adjacent vertebral end plates. Disc removal has to extend to the contralateral side. (G and H) The gap is closed by compression of the instrumentation. Cancellous bone of the hemivertebra is added for bony fusion.



Figs. 102.2A to G: (A) A 6-month-old girl with a fully-segmented hemivertebra L2a, Cobb angle 37°. (B and C) Increasing deformity at the age of 14 months: scoliosis 45° and kyphosis 29°. (D and E) Postoperative radiographs after resection of the hemivertebra and instrumentation with a cervical plate system at the age of 16 months. (F and G) The radiographs of the adult patient 16 years postoperatively.

resection, closes completely (Figs. 102.1G and H). Cancellous bone (bone material from the hemivertebra) may be added to facilitate bony fusion. The neural structures must be controlled and protected at all times during the resection of the hemivertebra as well as during the corrective maneuver.

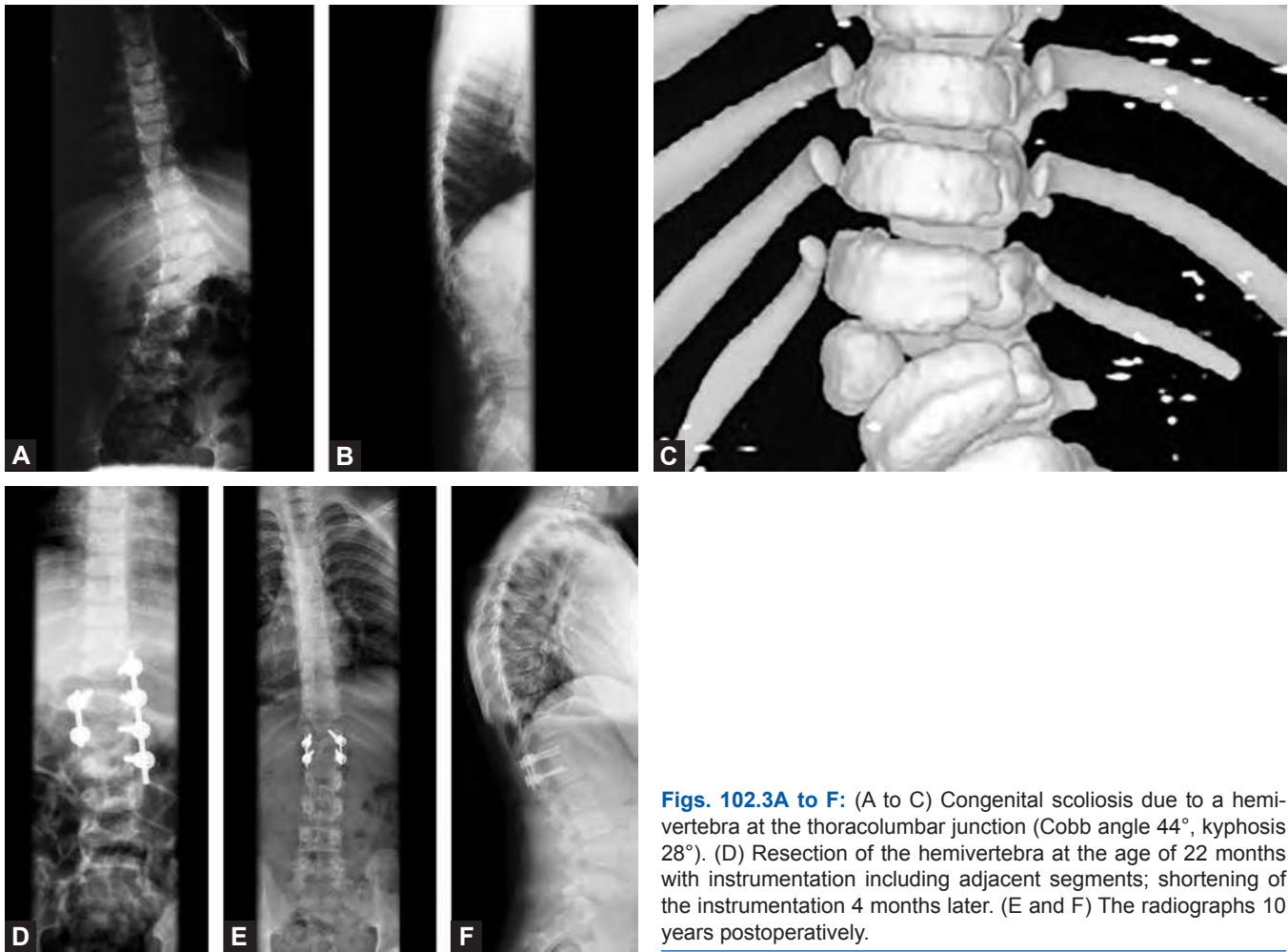
In cases of single hemivertebrae without bars, rib synostosis, or other major structural changes of the neighboring vertebrae, only the two vertebrae adjacent to the resected hemivertebra are fused (Figs. 102.2A to G). If a high amount of compressive force is necessary to correct the deformity, especially in cases with pronounced kyphosis, one or two additional segments should be permanently or temporarily included into the instrumentation to avoid overloading of the pedicles with subsequent pedicle fracture. If a temporary instrumentation is planned, the exposure of these additional vertebrae should be performed very carefully with preservation of the periosteum and the facet

joints. Three months after primary surgery, the instrumentation is shortened to the fused segments. The temporarily instrumented segments are released to regain mobility (Figs. 102.3A to F).

Spinal monitoring is essential for maximum safety especially during the correction maneuver.

Posterior Spinal Osteotomy: Surgical Technique

In patients with bony fusion adjacent to the hemivertebra, especially in older children or adults, or in patients with a contralateral bar-formation, a complete osteotomy of the spine is required to achieve a sufficient correction.^{32,42} In addition to the convex dissection at the apex with resection of the hemivertebra, an additional exposure of the synostosed vertebrae at the concave side via the posterior approach is performed. This access to the concave lateral



Figs. 102.3A to F: (A to C) Congenital scoliosis due to a hemivertebra at the thoracolumbar junction (Cobb angle 44° , kyphosis 28°). (D) Resection of the hemivertebra at the age of 22 months with instrumentation including adjacent segments; shortening of the instrumentation 4 months later. (E and F) The radiographs 10 years postoperatively.

wall of the spine has to be very oblique, as the spinal cord is usually shifted to the concavity and due to the rotation of the apical vertebrae.

In these patients, pedicle screws are placed in at least two segments above and below the planned osteotomy. In the thoracic spine, a bilateral costotransversectomy at the apex is performed. The proximal parts of the ribs including the rib heads are removed. In case of rib-synostosis at the concave side, a wide resection of the synostosed ribs is required to gain the very oblique access to the lateral wall of the vertebral body. The lateral aspect of the vertebrae is exposed by blunt dissection. A laminectomy is performed at the apex, including the lamina of the hemivertebra and partially the adjacent laminae, including a wide wedge of the synostosed laminae in case of defects of segmentation. The joint facets are removed, and the spinal cord and the nerve roots are identified.

The pedicles at the apex are removed. Then the wedge-shaped resection of the vertebral body is performed. The wedge comprises the body of the hemivertebra or, in segmentation defects, a wedge according to the desired angle of correction. The major portion of the vertebral body is usually removed from the convex side; however, to achieve mobility, the bar at the concavity must be cut or resected as well (Fig. 102.4). This part of the surgery may be demanding, as the spinal cord is usually tight at the concave pedicles. Thus, the approach to the concave part of the vertebral body has to be very oblique. To avoid bulging during compression, the posterior wall must be completely removed. The bilateral resection entails a complete disruption of continuity of the spine. It is therefore essential to place at least one rod on the contralateral side for stabilization during the osteotomy. When the resection is complete, correction is performed by closing

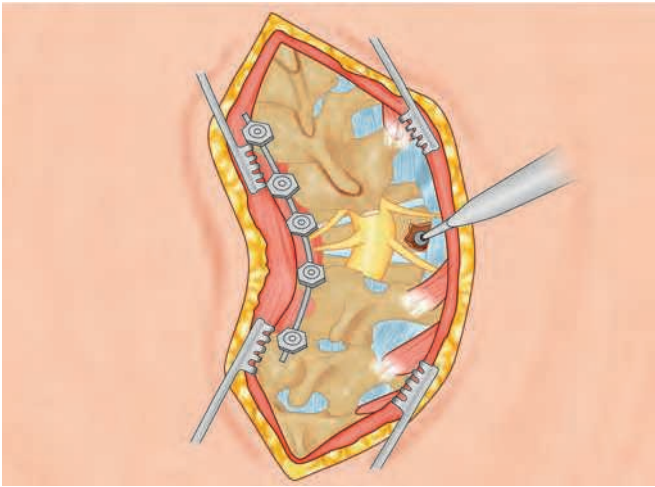


Fig. 102.4: Resection of a wedge-shaped apical vertebral body. One rod is in place to avoid a dislocation.

the gap by compression via the instrumentation. During this maneuver, the spinal cord must be thoroughly controlled to avoid any impingement. Spinal cord monitoring is imperative. Especially in kyphotic cases an anterior spacer is inserted that acts as a hinge for correction. The height of the spacer is ideal when after complete correction the length at the spinal cord is slightly shortened. Bone material from the vertebral body is added posterolateral for fusion.

Hemivertebra Resection at the Lumbosacral Junction

While in the thoracic and lumbar spine the resection of a hemivertebra via a single posterior approach is usually unproblematic, it may be more demanding at the lumbosacral junction. The access to the body of the hemivertebra is complicated by the iliac crest and the sacral ala, especially in male patients. In these cases, a combined approach starting with an anterior resection of the vertebral body is advantageous. A preoperative imaging and a meticulous intraoperative dissection of the iliac vessels is necessary (Figs. 102.5A to D).

Postoperative Management

Patients are mobilized within the first postoperative week. A brace is worn for usually 12 weeks. Radiographs are taken at 2 weeks, 3 and 6 months postoperatively. Radiographic examinations are performed once a year until

the end of growth. The implants should be left in place until the patients are skeletally mature to avoid the risk of increasing deformity despite bony fusion.

Hemivertebra Resection in the Cervical Spine

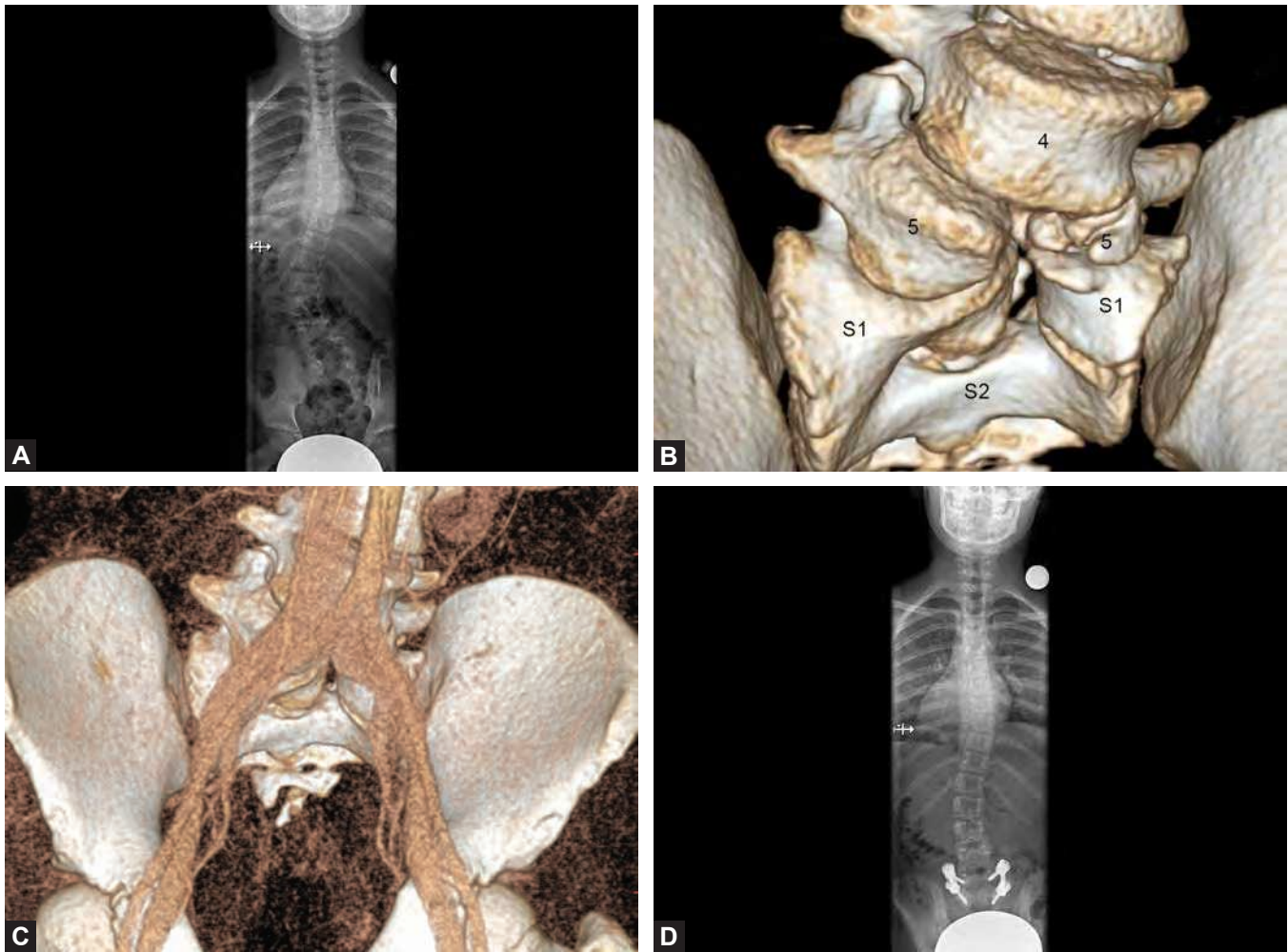
Congenital scoliosis due to a hemivertebrae is rare in the cervical spine. The deformity is often associated with additional anomalies like congenital block vertebrae (Klippel-Feil syndrome) and congenital scoliosis in the thoracic and lumbar spine.⁴³ Most patients present with restriction of neck motion, head tilt or torticollis, and asymmetric shoulder level. Especially in patients with Klippel-Feil syndrome, there is little possibility for compensation of scoliosis in the frontal plane. In an effort to keep the head straight with the eyes in a horizontal line, most patients develop severe compensatory curves in the thoracic region (Figs. 102.6A and B).

Surgical therapy therefore should be performed early in patients with severe disfiguring deformity or patients with proven or expected deterioration. Hemivertebra in the cervical spine (except C7) requires a combined posterior and anterior approach due to the course of the vertebral artery. A meticulous preparation of the spinal cord, the nerve roots, and the vertebral arteries is imperative. After complete resection of the hemivertebra the correction is achieved by closing the gap with anterior or posterior compression instrumentation (Figs. 102.7A to D).⁴⁴

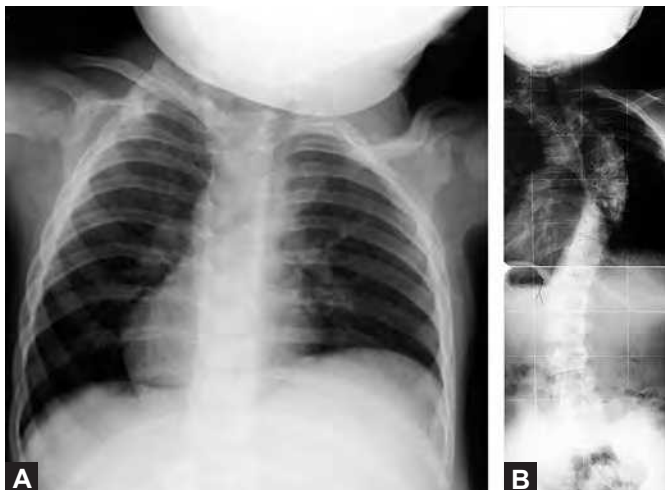
Growth Guiding Techniques

Children with multisegmentation defects or combinations of hemivertebrae, contralateral bar formations, and rib synostosis are the most challenging group of patients. These spinal deformities are usually rapidly progressive with a poor prognosis. Correction by means of osteotomies and fusion would require a long instrumentation, and may require inclusion of the structural secondary curves. The multisegmental instrumentation with fusion would induce a substantial growth deficit.

To address this problem and to minimize the growth deficit, a growth guiding or distraction device may be helpful. Possibilities are growing rod techniques, sliding rod systems, or, in case of predominant rib cage deformities, a rib distracting device.^{45,46} Depending on the type of deformity, a combination of different surgical procedures may be used



Figs. 102.5A to D: (A to C) A 12-year-old girl with an asymmetric butterfly vertebra at L5. Secondary lumbar curve of 50°. A precise imaging of the iliac vessels is necessary for planning the anterior approach. (D) Postoperative radiograph after the anteroposterior resection and fusion of L4 to S1. Spontaneous correction of the lumbar curve to 22°.



Figs. 102.6A and B: (A) A 2-year-old boy with hemivertebrae C3a and C7a at the left side. The thoracic spine is still straight. (B) Same boy at the age of 14 years: increasing deformity at the cervical spine and the cervicothoracic junction, compensatory structural curve of 79° at the thoracic spine.



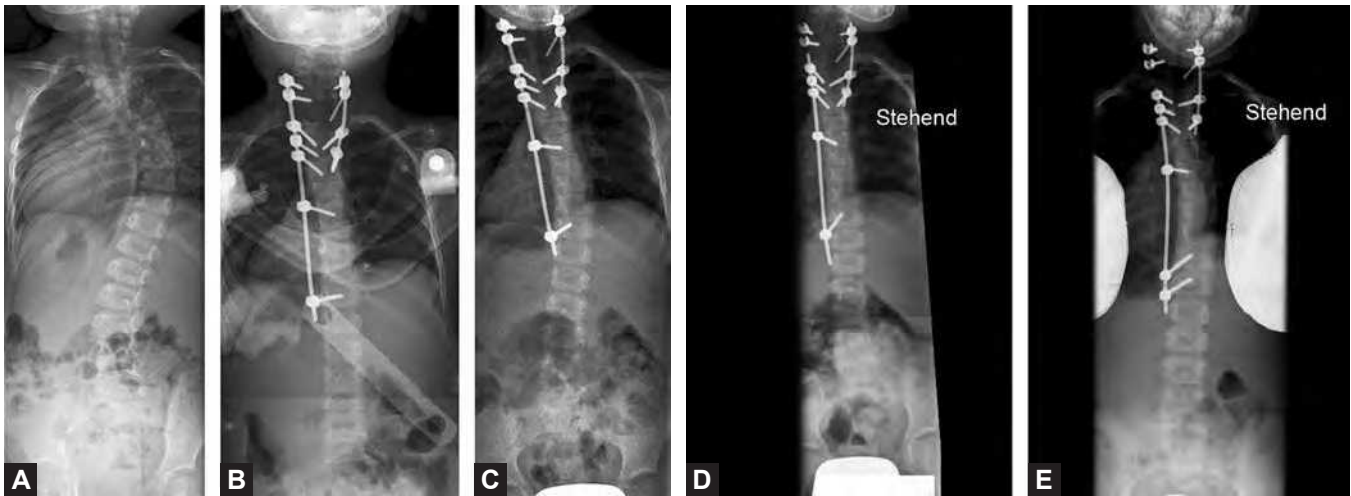
Figs. 102.7A to D: (A and B) Cervical scoliosis in an 8-year-old child due to a double hemivertebra (C2a + C4), atlanto-occipital synostosis, and block vertebra C5-C6. Scoliosis of 32°, head tilt 19°. (C and D) The radiographs 5 years after hemivertebra resection C4 by a posterior-anterior-posterior approach. Scoliosis of 7°, head tilt 5°.

to optimize the results. Hemivertebra resection with osteotomies and short fusion provides an excellent correction of the deformity at the apex. A supplementary growth-directing instrumentation may be added to guarantee normal growth of the adjacent spine. Such a combination of different procedures may achieve the optimum result with a straight spine and a minimal growth deficit (Figs. 102.8A to E). The key element of all growth preserving techniques is a very careful surgical technique with preservation of the periosteum and adjacent soft tissues. Injuries of the vertebral joints and very stiff implants increase the tendency to premature fusion. We have to be aware that the initially included spinal segment will be fused after the growth-guiding procedure.

SPINAL GROWTH FOLLOWING TRANSPEDICULAR INSTRUMENTATION

Transpedicular screws allow for the most stable fixation of vertebrae in spine surgery. Especially in very young patients where the connection between the posterior structures and the vertebral bodies via the neurocentral synchondrosis is still weak, the pedicle screws allow for a reliable fixation. A reliable fixation is fundamental for sufficient correction, short fusion, and early mobilization. The transpedicular instrumentation is able to transmit a high amount of compression force to the vertebral body to close the gap after resection of a hemivertebra.

However, crossing the neurocentral synchondrosis by transpedicular screws in very young children may give



Figs. 102.8A to E: (A) A 3-year-old girl with a congenital scoliosis at the cervicothoracic junction (hemivertebrae C7 and T3) and thoracic scoliosis. (B to D) Radiographs postoperatively, 12 months postoperatively, and after distraction. (E) Four years after the initial surgery with an additional screw and further distractions.



Fig. 102.9: Magnetic resonance imaging 7 years after transpedicular instrumentation in a 22-month-old child (same patient as in Figs. 102.3A to F): no stenosis of the spinal canal.

rise to objections concerning further growth of the vertebrae and the width of the spinal canal. Since 1991, several hundred transpedicular screws were inserted in 1- and 2-year-old children. None of these children developed neurological deficits during further growth. Magnetic resonance imaging and CT scans showed no spinal stenosis (Fig. 102.9).^{41,47} There was vertebral growth despite the instrumentation in longitudinal as well as in vertical direction. The posterior instrumentation may act as a tether leading to increasing lordosis (Figs. 102.10A to C).

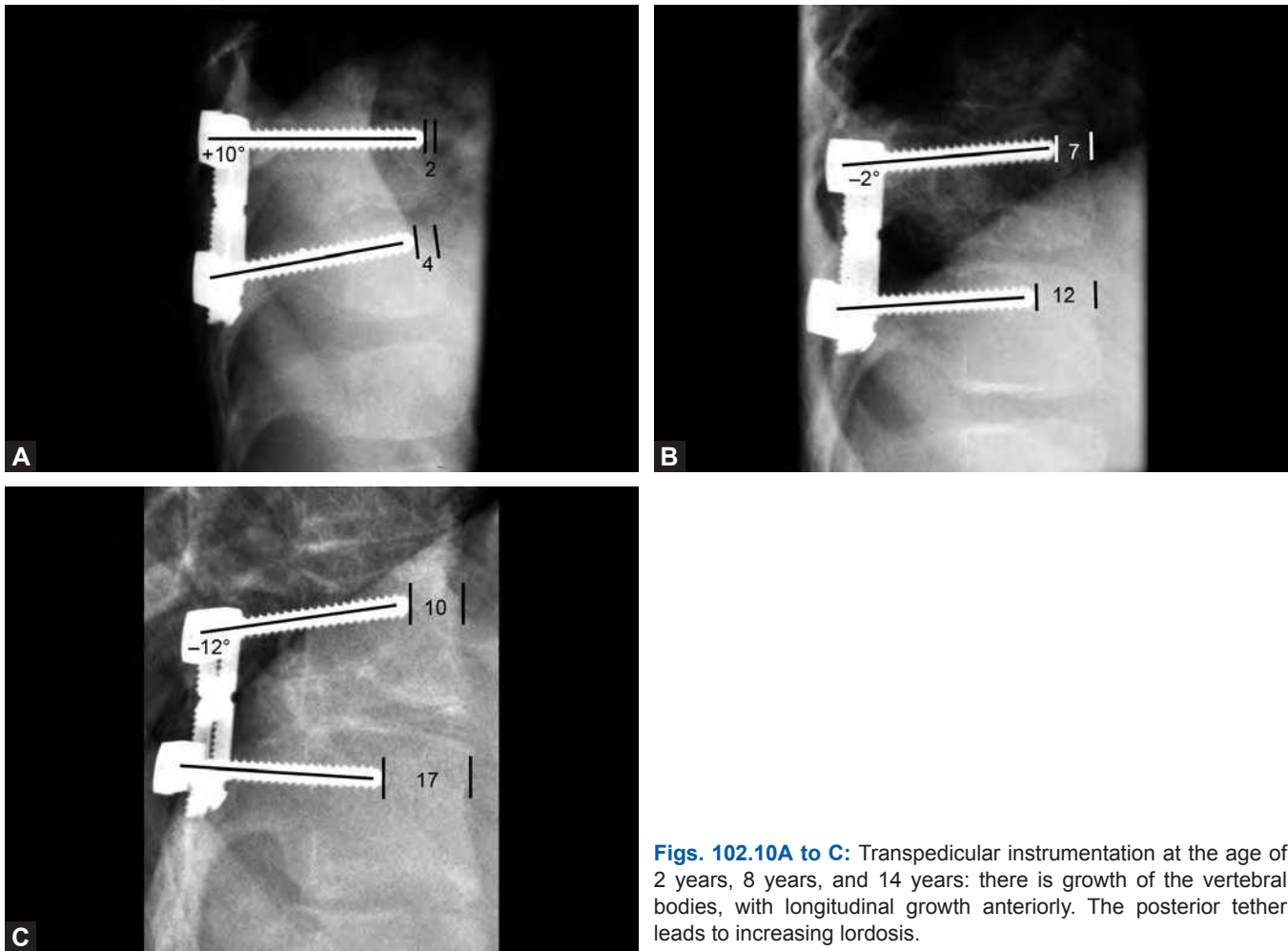
CONCLUSION

Treatment of congenital scoliosis in the growing spine is a challenging task. The goal of the treatment is to achieve a straight spine with a minimal growth deficit at the end of growth. Due to the wide variety of formation and segmentation failures, therapy for each patient has to be chosen individually depending on the type of deformity, the severity, and the expected progression. Planning of the therapy requires a precise imaging to classify the deformity, and a profound knowledge of the natural history of the spinal anomaly. Different surgical techniques are available like hemivertebra resection, spinal osteotomies and bar resections, growth guiding and distracting techniques. For the individual patient a combination of different techniques or a staged procedure may be useful to achieve the optimal result.

These are the key points for successful treatment:

- Maximum correction at the apex of the deformity in the frontal and sagittal plane
- Fusion as short as possible to minimize growth deficit
- High stability for early mobilization
- Early correction to avoid the development of secondary structural curves.

In case of a single hemivertebra without any additional anomalies resection of the hemivertebra is likely curative. With a complete correction and a short fusion, we may expect a normal further growth of the infused spine. The monosegmental fusion imposes no restrictions.



Figs. 102.10A to C: Transpedicular instrumentation at the age of 2 years, 8 years, and 14 years: there is growth of the vertebral bodies, with longitudinal growth anteriorly. The posterior tether leads to increasing lordosis.

In cases with severe combinations of formation and segmentation defects and possible rib cage deformities, the final result depends on the growth potential of the spinal segments. The residual growth should be used optimally. However, a certain amount of growth deficit compared to a normal spine may be inevitable.

For all patients with congenital deformities frequent follow-up evaluations are mandatory until the end of growth.

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Neuromuscular Scoliosis

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Snapshot

- » Principles and Goals
- » Etiology
- » Natural History
- » Patient Assessment
- » Preoperative Considerations/Comorbidities
- » Treatment Principles
- » Authors' Recommended Surgical Treatment Method
- » Intraoperative and Postoperative Considerations and Complications
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INTRODUCTION

Neuromuscular diseases are heterogeneous between and within diseases and are due to a vast number of pathologies involving the brain, spinal cord, peripheral nervous system, and muscle. The prevalence of spinal deformity is typically proportional to the severity of neurologic impairment. It may range from 5% in the spastic diplegic cerebral palsy child to 100% in the young child with spinal cord injury. Progression is common to the natural history of scoliosis in most neuromuscular diseases.^{1,2} Conservative treatment with bracing and/or wheelchair modifications is only temporary and does not prevent curve progression. Progression often also occurs after skeletal maturity.³ Curvatures over 60° begin to affect sitting and standing balance, head control, as well as pulmonary function. Pelvic obliquity may also occur and is secondary to the scoliotic deformity extending to the pelvis. Sagittal plane deformities can occur in combination with scoliosis or in isolation in neuromuscular disease. Isolated hyperlordosis and hyperkyphosis is less common than scoliosis, but can also cause seating problems and pain especially when >70°. ^{4,5}

Surgical management is warranted to improve the quality of life in neuromuscular disease. It is indicated in progressive curves when the child is not tolerating seating

(in nonambulators) or standing (in ambulators), or if the natural history of the neuromuscular disease predicts progression associated with the deterioration of pulmonary status. Surgery may also be indicated to alleviate pain or to correct pelvic obliquity prior to correcting a concomitant hip dislocation.

PRINCIPLES AND GOALS

The principles and goals for treating neuromuscular scoliosis are vastly different than idiopathic scoliosis. Children with neuromuscular disease often have multiple comorbidities, and a greater risk of mortality. The risk of the natural history of the neuromuscular disease must be weighed against the risk of the natural history of scoliosis progression for that specific neuromuscular condition and the risk of surgical intervention for the individual patient. How to balance these considerations mandates that the surgeons have an in-depth understanding of natural history of the neuromuscular condition and the risk of scoliosis progression for each neuromuscular condition as well as specific concerns impacting the patient and/or caretaker.

Despite the heterogeneity of neuromuscular conditions that are associated with neuromuscular scoliosis, there are a number of common issues to the treatment of these children:

- The importance of etiology in the natural history of the disease and the scoliosis
- Presence of comorbidities
- Nonoperative treatment is generally unsuccessful
- Rapid curve progression that may occur earlier in life
- Rigid curvatures
- Frequent pelvic obliquity
- Long C-shaped curvatures
- Loss of sitting or standing balance
- Concurrent hyperlordosis and hyperkyphosis
- Higher surgical risk/complications.

ETIOLOGY

Whether the neuromuscular disease originates from pathology involving the upper or lower motor neurons, the peripheral nervous system, or the muscle, neuromuscular scoliosis is a consequence of muscle imbalance. It occurs in patients with a wide variety of neuromuscular diseases that include cerebral palsy, poliomyelitis, myelomeningocele, spinal muscle atrophy, muscular dystrophies, myopathies, and infectious, metabolic and traumatic encephalopathy. Neonatal and prenatal causes of cerebral palsy are mainly related to prematurity and birthing problems, leading to various severities of deformity patterns. Postnatal trauma, metabolic encephalopathy, infections, toxicities, child abuse, and closed brain injury are often left with neurologic defects and in severe cases quadriplegic involvement significant to spinal deformities. Knowing the exact etiology is not always critical to care for child with neuromuscular disability or deformity; however, it is extremely valuable to understand whether the neuromuscular lesion is static or progressive. There are considerable concerns for the patient in terms of worsening sitting balance, respiratory function, rib-to-pelvic painful impingement, and loss of upper extremity function in striving to remain upright. The cause of scoliosis is directly related to the severity of the neurological deficit. It is not exactly clear which component of neurological control is directly responsible for the spinal curvature; nevertheless, the most severely involved neurologically deficient patients have most severe scoliosis. Poor muscle control in the growing spine is the primary etiology, with spasticity, muscle weakness and poor balance are also substantial contributing factors.

NATURAL HISTORY

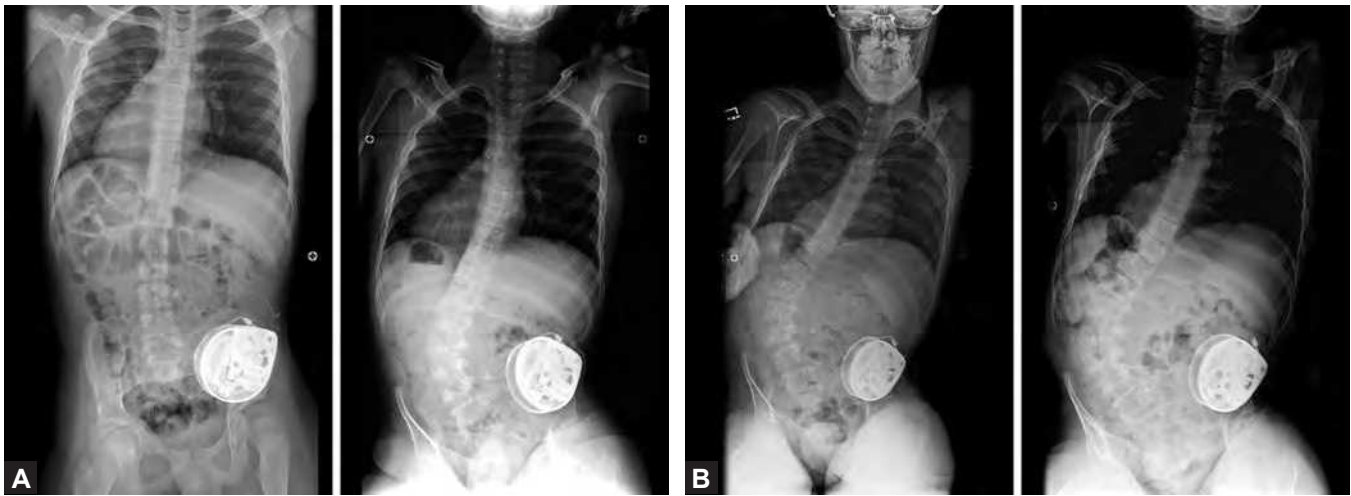
In general, the greater the severity of the neuromuscular involvement, the greater the prevalence, the earlier the onset, and the greater the risk of more rapid progression of the

scoliosis. The scoliosis or sagittal plane spinal deformity in general is due to muscle imbalance of low or high tone and abnormal postural reflexes. Its frequency ranges from 25% to 90% depending on the associated disorder.⁵ Curve patterns are most commonly lumbar or thoracolumbar with associated pelvic obliquity. Scoliosis in the patient with neuromuscular disease is rarely present in early childhood, and when it is present, it is typically flexible and lacks significant structural components. On occasion, a structural curve may occur at an early age of 2 or 3 years. Treating physicians must be aware that these curves may advance fairly rapidly in magnitude and stiffness for these patients (Figs. 103.1A and B). The natural history of both the neuromuscular disease and the scoliosis within each disease is critically important for the surgeon to understand the impact that the scoliosis will have on the child's longevity and quality of life. In addition, the natural history of the disease impacts the associated comorbidities, surgical timing, and the subsequent risks associated with surgery.

PATIENT ASSESSMENT

With the consented decision of the family to proceed with the surgery, adequate preoperative workup must ensure that all medical conditions are under maximum medical management. All children with neuromuscular conditions should have a detailed preoperative assessment. Patients with neuromuscular disease often have associated medical comorbidities that correlate strongly with postoperative complications and include gastroesophageal reflux, restrictive lung disease, aspiration pneumonia and reactive airway disease, heart disease, poor nutrition, the presence of a seizure disorder, and low bone mineral density. These should be identified in the medical history and preoperatively, and comanaged medically.⁶

Physical examination should assess sitting and standing balance, pelvic obliquity, curve stiffness, and the spinal deformity's coronal, sagittal, and rotational components. The orthopedist should also evaluate for the coexistence of hip subluxation or dislocation. Curvatures that are stiff in both the coronal (scoliosis) and sagittal planes (severe hyperlordosis and hyperkyphosis) may require anterior^{6,7} release or preoperative traction.⁸ The side-bending test is helpful for assessing coronal plane stiffness (Fig. 103.2). Sagittal plane stiffness should also be assessed by seeing if kyphosis will reduce in the supine position over a bolster and assessing the flexibility of hyperlordosis by hyper-reflexing both hips and the pelvis in the



Figs. 103.1A and B: This is a boy with quadriplegic cerebral palsy who developed progressive scoliotic curve of 7° to over 90° within 18 months.

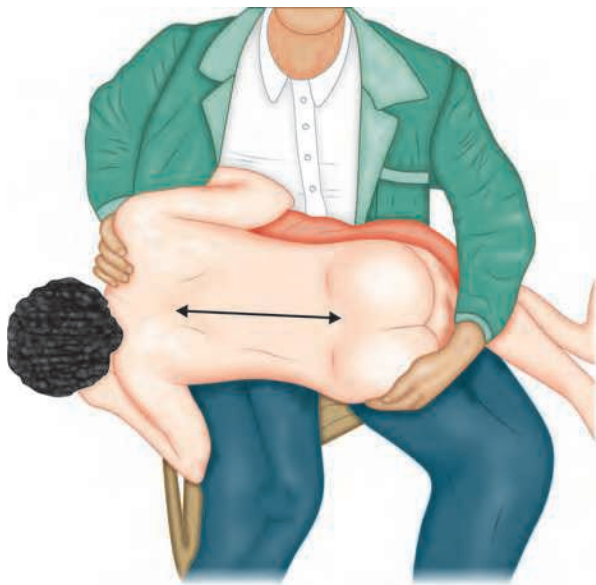


Fig. 103.2: Side-bending test for assessing coronal plane stiffness.

supine position. If the deformity cannot be reduced in either plane, anterior discectomy should be considered. It is important to assess and distinguish the coexistence of a hip flexion contracture and adduction contracture in the high-tone neuromuscular conditions (e.g. cerebral palsy) with spinal deformity. This can be done by stabilizing the pelvis in a neutral position (flexing the opposite hip to level the pelvis to detect hip flexion contracture and assessing hip abduction with the pelvis in neutral obliquity). If these contractures are present, the parents should be warned

that muscle releases may be necessary 4–6 months after spinal surgery. The surgeon must also assess the need for fusing to the pelvis. In the cerebral palsy patient, this is almost always necessary to prevent distal extension (late pelvic obliquity) of a curvature fused to short. Patients with poor “righting reflex” (ability to center the head over the center of the sacrum) should be fused from T1 to the pelvis. Standing or sitting anteroposterior (AP) and lateral radiographs are important not only to measure curve magnitude, but to look at balance. Coronal and sagittal bending films, and traction films are operator-dependent and if done correctly can give important information about curve flexibility. Finally, the child should also have a detailed neurological examination that includes sensory and motor testing, and reflexes including abdominal reflexes to establish baseline neurological function and the need to look for any undiagnosed intraspinal pathology such as tethered cord or syringomyelia.

PREOPERATIVE CONSIDERATIONS/COMORBIDITIES

Patients with neuromuscular disease often have associated medical comorbidities that correlate strongly with postoperative complications and include the presence of cardiac disease, gastroesophageal reflux, restrictive lung disease, reactive airway disease, aspiration pneumonia, poor nutrition, the presence of a seizure disorder, and low bone mineral density. Preoperatively, these should be identified and medically comanaged.⁶

Nutritional and Gastrointestinal Problems

Children with neuromuscular disorders may have poor oral motor function and therefore poor nutritional intake. In addition, some children may have poor intestinal absorption. Poor nutritional intake may lead to higher infection rates and low bone mineral density in patients with neuromuscular disease causing poor surgical outcomes. In children with cerebral palsy and other spastic neuromuscular conditions, increased spasticity may increase nutritional requirements causing weight loss. Gastrostomy-tube (G-tube) placement is often helpful for long-term nutritional management. Gastroesophageal reflux is common in children with neuromuscular disease and may lead to chronic esophagitis resulting in failure to thrive as well as chronic aspiration leading to pneumonia. Some children may benefit from funduplications and/or jejunal feedings to prevent reflux. The involvement of the nutritionist and gastroenterologist is important to optimize preoperative nutrition and minimize postoperative complications. There are no specific nutritional criteria that would exclude surgical intervention; however, children with no subcutaneous fat, poor food intake, and poor body weight for height ought to have nutrition enhanced by feeding supplementation, including that of nasogastric tube feeding. Finally, there is no good evidence of a particular nutritional level preoperatively that matters if aggressive postoperative nutrition is carried out.^{9,10}

Pulmonary

Pulmonary disease in the child with neuromuscular disease falls into two primary categories: reactive airway disease and restrictive lung disease. The former is usually a result of gastroesophageal reflux and chronic aspiration of gastric contents and/or saliva. In addition to the management of gastroesophageal reflux, tracheal diversion may be necessary to prevent aspiration of saliva.

Restrictive lung disease is more common in flaccid neuromuscular disease [see special considerations under: Duchenne muscular dystrophy and spinal muscular atrophy (SMA)]. Early surgical management and ventilator treatment may help delay respiratory failure in these children. Comanagement with a pulmonologist is imperative to preoperative management.

Cardiac

Preoperative cardiac workup should be considered in all children with neuromuscular disease with curvatures $>80^\circ$ and in children with, Duchenne muscular dystrophy, Friedreich ataxia, and certain myopathies.

Endocrine

At our institution, some children with upper motor neuron disease have been discovered to have deficiencies in thyroid hormone, cortisol, while others may have more significant endocrinopathies (e.g. panhypopituitarism). If clinically indicated, these should be investigated and addressed prior to any surgical intervention of the spinal deformity.

Neurologic

Many children with neuromuscular disease have seizure disorders. Adequate seizure medication levels should be obtained prior to surgery and comanaged by the neurologist. In addition, some patients with neuromuscular disease, especially those with myelodysplasia have ventricular-peritoneal shunts. Intraventricular shunts should be checked with radiographs and computed tomography (CT) scan to make sure that they are not broken and are functioning (Fig. 103.3). If the shunt is still needed, it should be checked by the neurosurgeon preoperatively.



Fig. 103.3: Malfunctioning ventricular-peritoneal shunt found to be broken.

Bone Density

A final preoperative consideration is the bone density of the child with neuromuscular disease undergoing spinal fusion. The child who is poorly nourished, nonambulatory, and on seizure medication is at greatest risk. In the child with low bone density, instrumentation may be difficult with a possibility of sublaminar wires cutting out and pedicle screws pulling out of osteopenic bone. Children on seizure medications should have vitamin D, calcium, phosphorus, and alkaline phosphorous levels checked. Nonambulatory children with a history of low-impact type long-bone fracture should undergo bone density measurement using dual-energy X-ray absorptiometry (DEXA scan). Children with measurements two or more Z scores below the mean should be considered for treatment with bisphosphonate therapy such as with intravenous (IV) pamidronate.

TREATMENT PRINCIPLES

Bracing

Nonoperative treatments have not had any documented impact on the progression or eventual outcome of neuromuscular spinal deformity. It is important, nevertheless, to address the conservative modalities that may provide some temporary beneficial use in maintaining upright sitting.

Seating adaptations such as hip guides and offset chest lateral seat supports may temporarily improve sitting in wheelchairs or other seated devices. This is especially helpful in very young children with flexible curvatures. Hip guides serve to capture the pelvis while offset chest laterals with one on the convex side at the apex of the curve and another one placed just below the axilla on the concave side of the curve serves as a three point “corrective” force to hold the patient upright (Fig. 103.4).

Neuromuscular scoliosis has not shown beneficial response to bracing demonstrating no change in the rate of progression or final outcome of the magnitude or stiffness of the spinal deformity.¹ Some children have been braced for as long as 14 years, kept in brace wear for 23 hours a day in facilities with exceptional documentation and still developed typical scoliosis of the same magnitude and stiffness.¹¹ Higher magnitude yet still flexible curves in younger children may require the additional support of bracing in order to delay surgery while still maintaining upright sitting posture. A soft thoracolumbosacral orthosis (TLSO) jacket that is well padded to prevent any skin



Fig. 103.4: Hip guides and offset chest laterals placed one of the apex convexity and another placed below the axilla on the concavity serve as a three-point corrective positioning force to keep the boy upright.



Fig. 103.5: Bracing may provide upright positioning support yet have little to no effect on curve progression.

breakdown can be easily applied and removed (Fig. 103.5). Caretakers should be educated that the orthosis will not benefit the structural scoliosis curve, therefore should be used only at times when it is providing children direct functional benefit such as when they are in their wheelchair. In fitting these children into their wheelchairs with the

brace in place, wheelchair modifications may be necessary when the children are in the brace yet the chair may not fit properly without the brace. In such cases, the family and caretakers may need to decide if they want the child in the brace almost entirely when seated, or if they want to use it only for specific seating aside from in the wheelchair. Problems with bracing may include discomfort in warm weather, pressure sores, and restriction of the child's breathing ability. Another restrictive concern may occur during feeding, particularly in children who are tube-fed and have gastroesophageal reflux. In these incidences, the orthotic may be loosened or simply removed during and for an hour period after feeding. It is also important that the family's expectations be clearly addressed as to not gain the false hope that the orthotic use will alter the rate and eventual progression of the spinal deformity.

Surgical Treatment

The principles of spinal deformity correction in neuromuscular scoliosis are to: (1) correct pelvic obliquity by leveling the pelvis with the sitting or standing surface, (2) restore trunk balance, (3) center the head over the trunk and pelvis, (4) restore sagittal balance (lumbar lordosis and thoracic kyphosis including the correction of anterior and posterior pelvic tilt, respectively), (5) maximize segmental fixation in the face of what is often osteoporotic bone, and (6) minimize operative time in this patient population who often have multiple comorbidities and who are at greater risk for wound infection. Rotational correction is less important unless the rotational deformity is affecting pelvic or trunk balance.

Posterior Fixation

The gold standard for surgical instrumentation in the treatment of neuromuscular scoliosis is Luque rod instrumentation with Galveston extension to the pelvis, cross-linkage (to prevent rod rotation and shift of the rods) with sublaminar wiring.¹² Surgical correction using both pedicle screw and hybrid fixation has also been successful in obtaining adequate correction.^{13,14} Other methods of pelvic fixation in neuromuscular scoliosis have been used to address associated pelvic obliquity.^{15,16} The unit rod incorporated these concepts into one unit and serves as a very powerful cantilever to correct scoliosis^{17,18} (especially lumbar and thoracolumbar curves) and pelvic obliquity. Technical difficulties with the unit rod include difficulty with pelvic limb placement (especially with hyperlordosis), problems

judging final rod length proximally, inadequate correction of severe rotational deformity, and having sufficient lever to correct upper thoracic scoliotic and kyphotic curves. More recently, the combination of pelvic screws, precontoured rods, properly placed cross-connectors plus sublaminar wire, and/or pedicle screws has allowed greater modularity and can minimize the technical difficulties of the unit rod.

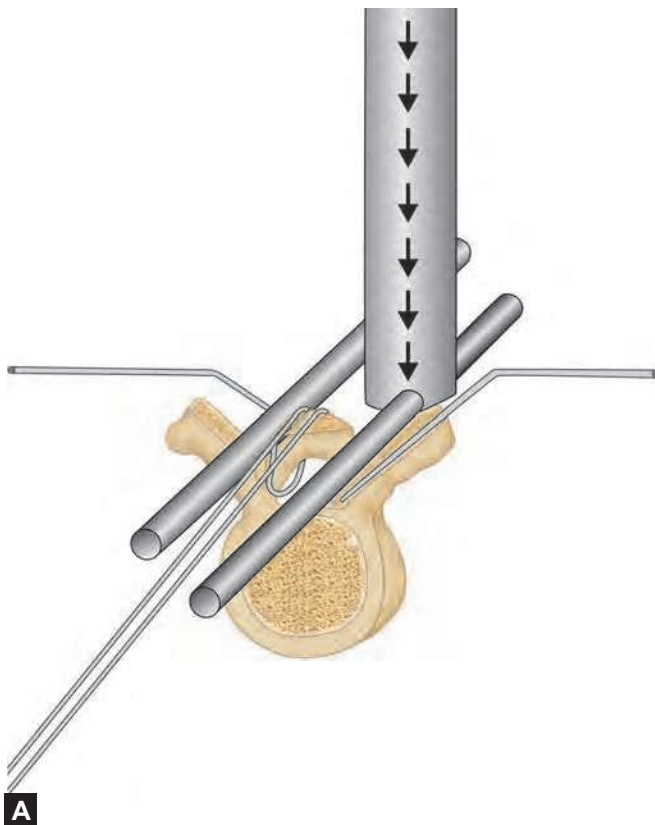
AUTHORS' RECOMMENDED SURGICAL TREATMENT METHOD

Correcting Pelvic Obliquity

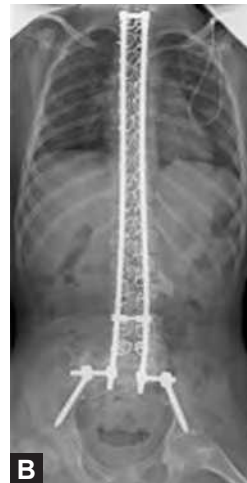
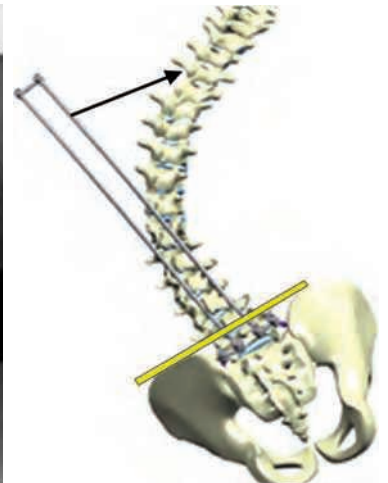
Fixation and fusion to the pelvis should be considered in every cerebral palsy patient to prevent late pelvic obliquity. Cantilever correction is a powerful method to correct pelvic obliquity^{7,19,20} (Dias 1996, Rinsky 1990, Tsirikos 2008). It requires instrumentation that can firmly anchor into the pelvis and can then be used as a lever arm to swing the pelvis into a corrected position that is perpendicular to the longitudinal axis of the spine. Traditionally, the unit rod (Fig. 103.6) is ideal for this purpose; however, it can be difficult to place the pelvic limbs of the rod in cases of severe pelvic obliquity and/or lumbar lordosis ($>70^\circ$), because it must be placed into the pelvis in one unit. Cantilever correction using pelvic screws connected to dual precontoured rods connected by a proximal connector (Figs. 103.7A and B) can also accomplish this. The pelvis is exposed by dissecting up over the sacroiliac joint



Fig. 103.6: The unit rod comes in variety of lengths for usage in neuromuscular scoliosis instrumentation.

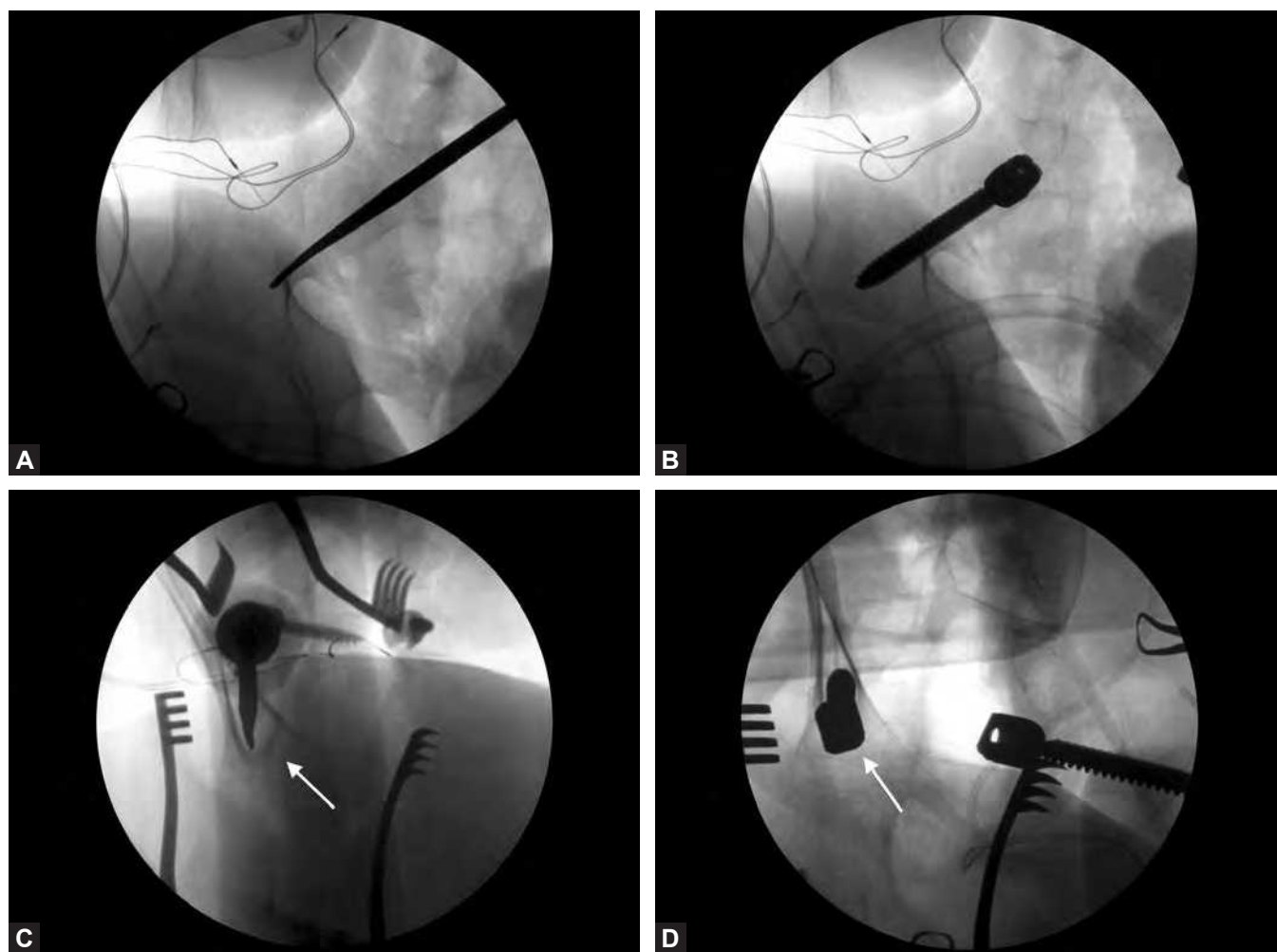
**A**

Figs. 103.7A and B: The unit rod construct is pushed down manually at each level with the rod pusher prior to tightening the sublaminar wires, if used. If pedicle screws are used, it is still important at each level to push the rod down gradually to prevent plowing out of the screws. The spinous process must be kept centered between the rods.

**B**

onto the lumbar muscle attachment on the inner table of the pelvis. It is important not to dissect into the sacroiliac joint subperiosteally, as one can encounter significant bleeding here. By dissecting over the joint itself, little bleeding is encountered. The muscle is then sharply and bluntly dissected up over the iliac crest apophysis. The overlying fascia is then divided and the outer wing of the ilium is then subperiosteally exposed from the posterior superior iliac spine (PSIS) forward along the posterior one third of the pelvis and down to the sciatic notch. A guide that hooks into the sciatic notch is then utilized to aim a drill hole from the PSIS start point to just anterior and superior to the sciatic notch. If a guide is not available, the pedicle probe alone can be used and aimed just above the sciatic notch by direct palpation or by using intraoperative fluoroscopy. This is the region where the pelvis is most dense for pelvic rod or screw fixation.²¹ Intraoperative AP and oblique fluoroscopic views

(Figs. 103.8A to D) are taken to confirm the trajectory of the drill or probe to make sure that there is no penetration of the inner or outer pelvic table. Pelvic screw fixation of largest diameter possible (usually 7–10 mm diameter) is placed in this trajectory and should be of sufficient length to pass the sciatic notch by at least 1 cm. The authors prefer the use a closed polyaxial screw head to maximize the rigidity of the final rod-pelvic screw construct. Typically, we use pelvic screws alone; however, when additional fixation is needed to improve the rigidity of pelvic fixation, then we add S1 screws. We prefer this over sacral screw fixation alone, because pelvic screw fixation provides a better lever arm to correct both pelvic obliquity and sagittal plane pelvic deformity. Alternatively, pelvic screws can be placed using the medial portal as described by Sponseller.^{17,18} Advocates for this method state that there is less exposure time, less bleeding, and that the screw head is less prominent. While we have not found



Figs. 103.8A to D: Intraoperative fluoroscopy is used to obtain appropriate trajectory when drilling pelvic holes from the posterior superior iliac spine (PSIS) forward along posterior one-third of the pelvis to just anterior and superior to the sciatic notch. (A) Anteroposterior view shows the trajectory of the pedicle probe from the PSIS to just superior and adjacent to the sciatic notch. (B) Final screw position at least 1 cm lateral to the notch. (C) Oblique view shows the probe (arrow) and (D) final screw position between the inner and outer cortex just superior to the sciatic notch that appears as a “teardrop” (arrow).

bleeding or exposure time to be less in our hands, the screw is less prominent using this approach. We have obviated the screw head being prominent at the PSIS start point by notching the ilium at the entrance point with a rongeur and countersinking the screw. A fixed lateral rodded connector (usually 10 or 20 mm) is then used to connect each pelvic screw to a precontoured rod. Critical to the correction is to attach and secure each of the precontoured rods to the iliac screws with the fixed lateral connectors so that each of the rods is perfectly perpendicular to the horizontal axis of the pelvis and that the sagittal contour of the rods is aligned with the sacrum (Fig. 103.9). The sagittal bend should be identi-

cal on each rod and should also be aligned so that the contour matches from proximal to distal. If these steps are not meticulously done, the pelvic obliquity will not be fully corrected with the cantilever maneuver. Once this is done, the set screws on both the pelvic screws are tightened and torqued down onto the rod. A proximal connector is added at the top of the construct that strengthens the proximal construct. A drop entry cross-connector can be added in the lumbar spine to augment the stability of the construct.

Only if the patient has a leveled pelvis and adequate balance (“righting reflex”) should the surgeon consider ending fixation more proximal at L4 or L5. If fixation

to the pelvis is not done, fixation in the lumbar spine at a minimum of three levels with pedicle screw fixation is recommended. Cantilever correction and fixation to the remainder of the spine using screws or sublaminar wires can then be utilized.

Restore Trunk Balance

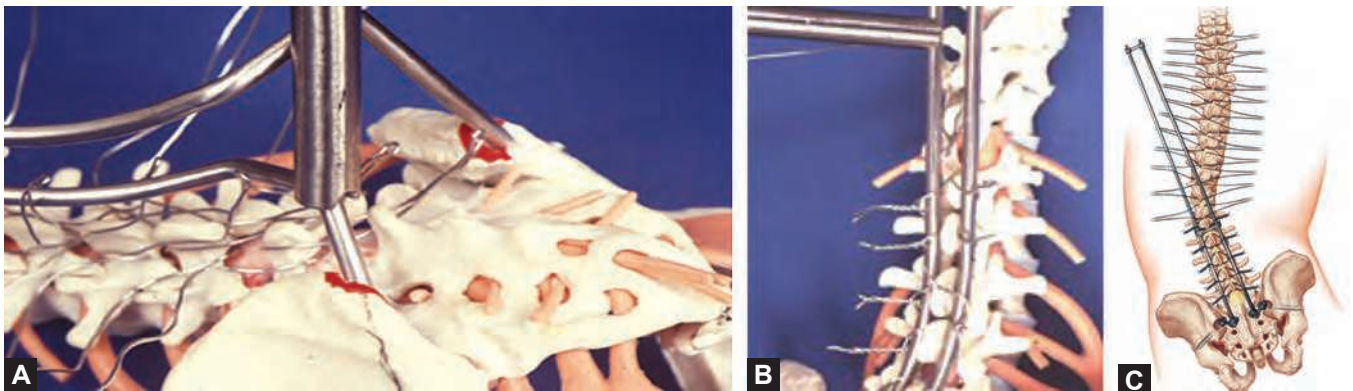
Trunk imbalance is most problematic in lumbar and thoracolumbar curves. Balancing the trunk is achieved with cantilever correction from distal to proximal. After the rod construct is “built” from distal to proximal as described above, cantilever correction can be started in order to correct pelvic obliquity and restore trunk balance. This begins by the surgeon pushing the rod down to the L5 lamina only

and then tightening the wire to the rod (a jet wire twister is helpful). Never use the wires to pull the rod to the spine. This is repeated in a step by step manner: push the rod down to the L4 lamina and then tighten down the wire, next the rod is pushed down to the L3 lamina and tighten the wire. The process is repeated one level at a time up to the T1 lamina (Figs. 103.10A to C). The wires are cut 1 cm in length and then bent and impacted down to the midline so as not to remain prominent. Just prior to tightening the wires at the proximal couple levels, the rod can be cut at the T1 level and the closed connector brought up to the proximal end of the rod and retightened and torqued, then final wire tightening. Alternatively, pedicle screws alone or a hybrid construct can also be used as segmental fixation points.

In cases where severe rotation is present (in the trunk or pelvis) and it is significantly impacting sitting or standing balance, pedicle screws should be used around the apex of the curve instead of sublaminar wires. Polyaxial reduction screws are recommended for the concave pedicles of the apical vertebrae in scoliosis or for both pedicles in hyperlordosis (see Fig. 103.11). Suggestions for poly versus uniplanar screws suggest reduction screws for hyperlordosis or all concave lumbar screws. Cantilever correction is then performed first, securing the rod to the spine with sublaminar wires or pedicle screws (depending on the level). A derotation maneuver at the level of the pedicle screws is then performed after the cantilever correction. It is important to have screws placed in at least 4–5 vertebral levels around the apex in order to distribute the derotational force and prevent plowing of the screws within bone that is often osteoporotic.



Fig. 103.9: The lateral connection to the iliac screws should make the rod perpendicular to the horizontal axis of the pelvis to maximize the cantilever correction.



Figs. 103.10A to C: The cantilever correction can be started after the rod construct is built from distal to proximal to correct pelvic obliquity and restore trunk balance. In step-by-step manner, the rod is pushed down to the lamina only and then the wire is tightened to the rod with a jet wire twister. Care must be taken to never pull the rod to the spine using the wires.

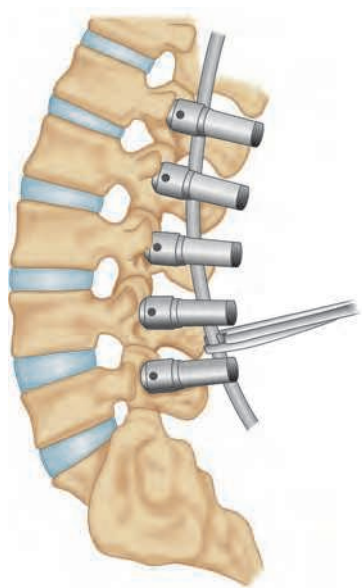


Fig. 103.11: Reduction of hyperlordosis can be achieved using pedicle screws with reduction posts.

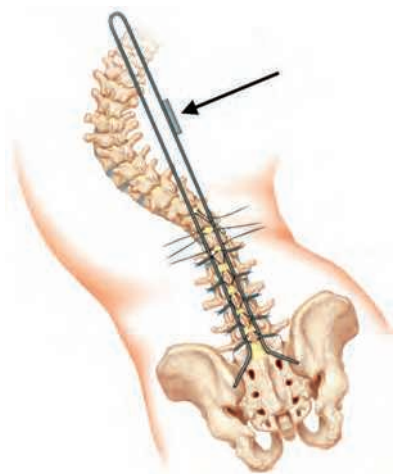


Fig. 103.13: Due to insufficient lever arm, it is difficult to cantilever this type of thoracic curve to the unit rod.

Restore Sagittal Balance

Restoring sagittal balance is critical. Excessive kyphosis or lordosis may occur with or without the presence of scoliosis. Pedicle screws with reduction posts are placed in the region of the hyperlordosis (usually the lumbar spine).²² After securing them to the pelvis with pelvic screws (as described in the section on correcting pelvic obliquity), the precontoured rods are pushed down into the reduction post and secured with the set screw. Reduction of the

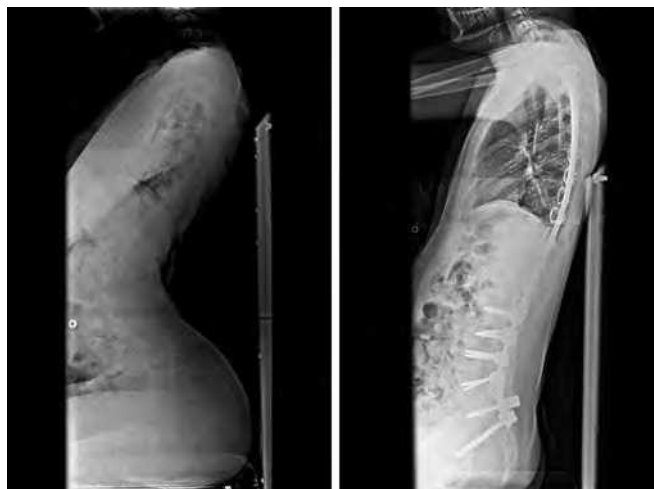


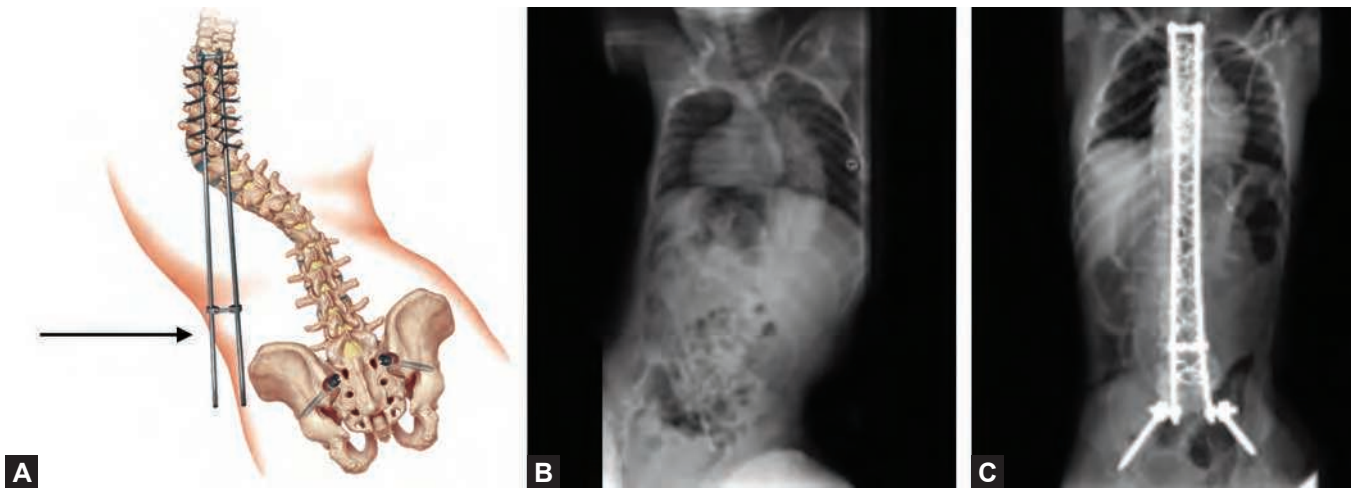
Fig. 103.12: Radiographs of a boy with hyperlordosis before and after surgical correction.

hyperlordosis is achieved by gradually screwing down the set screws (Fig. 103.11). Great care is taken to notice any evidence of posterior plowing of the screws. Dialing up the diameter of the screws may help with improved pedicle fixation. In addition, a sublaminar wire can be placed at the same level for additional fixation. Once the hyperlordosis is reduced, the remainder of the spinal instrumentation is completed, usually with sublaminar wire fixation (Fig. 103.12).

Hyperkyphosis can also be corrected using either a “distal to proximal” (in cases of lumbar or thoracolumbar kyphosis) or “proximal to distal” cantilever technique (in the case of a thoracic kyphosis). It is critical that fixation be completed up to at least T1 and occasionally C7 level to prevent “drop off” at the cervicothoracic junction. Firm fixation at the proximal-most end with two wires is recommended.

Centering the Head

The head being off center is most problematic in thoracic curvatures. Spinal curvatures in the thoracic region are more difficult to correct with cantilever correction. In such cases, starting distally at the pelvis or in the lumbar spine leaves a short lever arm at the proximal end of the rod by the time one reaches fixation in the thoracic spine. This makes it very difficult to center the head over the remainder of the thorax and pelvis. This type of curvature is very difficult to correct with the traditional unit rod since the unit rod requires distal fixation into the pelvis first (Fig. 103.13). With this type of curvature, fixation using the dual precontoured rods with proximal connector can be started



Figs. 103.14A to C: For thoracic scoliosis, proximal to distal cantilever technique can be used as demonstrated in the radiographs before and after surgical fixation.

proximally first. After exposing the spine and pelvis (in cases where pelvic fixation is required), pelvic screws and sublaminar wires are placed as previously described. The rod construct is then preassembled by first connecting the precontoured rods with the proximal closed rod connector at the top and placing a cross-connector in the lumbar region. The rods should be parallel from proximal to distal with respect to their contour. Next, the top of the rod construct is secured using sublaminar wires from T1 down to the apex of the curvature. After the apical vertebrae are secured to the rod, cantilever correction can be performed by gradually pushing the rod down to the next more distal vertebrae, tightening the sublaminar wire, pushing the rod down to the next more distal vertebrae and then tightening the wire, performing the same maneuver progressively down the spine until the pelvic screws are reached (Fig. 103.14). The fixed rodded lateral connectors are then utilized to connect the rod to the pelvic screws. Using this “proximal to distal” cantilever technique for cantilever correction allows for a better lever arm to correct thoracic scoliosis as well as thoracic kyphosis (Fig. 103.15), and to center the head over the trunk.

Maximize Fixation in Face of Osteoporotic Bone

As mentioned previously, quadriplegic cerebral palsy patients with severe osteoporosis require full evaluation of the bone density using DEXA scanning. In addition, evaluation of the vitamin D metabolism should be performed

by obtaining a full vitamin D panel, calcium, phosphorous, and alkaline phosphatase levels. Preoperative treatment may be necessary with several courses of IV pamidronate (in cases of osteoporosis) or with vitamin D (in cases of osteomalacia, usually secondary to seizure medication). Sublaminar wire fixation is preferred since the lamina has been shown to be biomechanically stronger than screws.²³ If screw fixation is necessary such as in cases of hyperlordosis or severe rotation, sublaminar wire fixation can be added at each level of screw fixation to add strength to the screw fixation points. In my own experience, this has been most commonly necessary at the L5 level. Alternatively, newer cortical fix pedicle screws may be used to help prevent this (Fig. 103.16). Also, dialing up the size of the pedicle with Clements pedicle dilators allows a bigger screw and better pedicle cortex fixation. Pedicle screw cement fixation can also be considered.

Minimizing Operative Time

Minimizing operative time is crucial, because the longer the spine is exposed, the higher is the risk of bleeding and infection. In general, passing sublaminar wires is faster than pedicle screw fixation and is more cost-effective in most surgeons’ hands who are well trained in both techniques. Most routine neuromuscular spinal deformity corrections can be performed with segmental sublaminar wire fixation alone. It is also more cost-effective than screw fixation. When pedicle screw fixation is performed, it is limited only to the levels that are needed, usually around



Figs. 103.15A to C: For thoracic kyphosis proximal to distal, cantilever technique can be used, shown in the radiographs before and after spinal fusion.

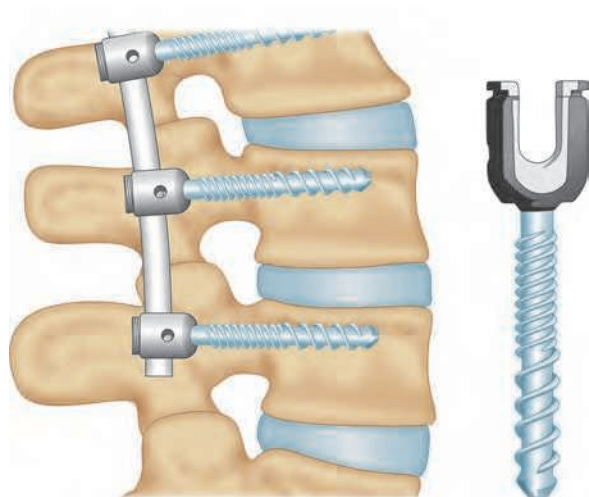


Fig. 103.16: Screw design of the cortical fix pedicle screw.

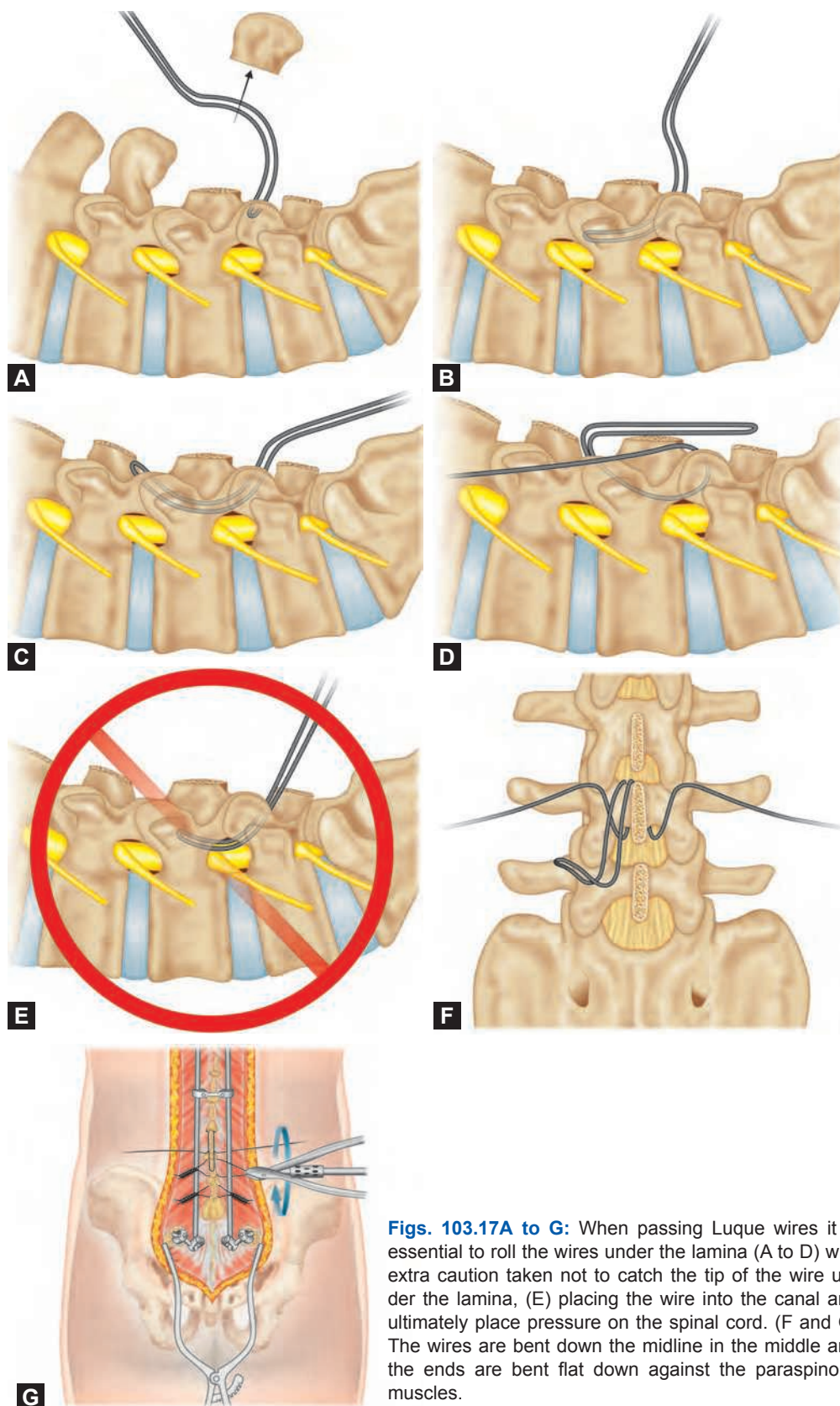
the apex of the scoliotic curve or in the region of hyperlordosis. In the case where epidural bleeding is problematic, pedicle screw fixation can also be considered to avoid more epidural bleeding. In our experience, however, epidural bleeding can be minimized by limiting removal of the ligamentum flavum to the central portion and avoiding going too lateral where the veins are more prominent. When epidural bleeding does occur, the application of surgifoam and thrombin usually stops it. Other consideration for minimizing the operative time includes careful preoperative assessment of curve stiffness. It is always best to consider scoliosis curve correction when the curve is under 70° and still flexible and therefore technically easier.

Sublaminar Wire Passage (Figs. 103.17A to G)

After the spine is completely exposed, the spinous processes are completely removed and the ligamentum flavum is carefully removed to expose the sublaminar spaces. Double Luque wires are bent (prebent wires are also available) and passed under the lamina of L5 up to and including the T1 lamina. The radius of curvature for the wire bend must approximate the width of the lamina to allow safe passage of the wire. Two double wires are passed at the L5 and the T1 lamina only while single wires are passed at each of the other levels. The wires are pulled up to equal length and then bent, with the midline bent flat down onto the lamina and the beaded end flat down onto the paraspinal muscles. This helps prevent the wires from getting inadvertently pushed into the spinal canal and allows for easier wire organization.

Anterior Release for Stiff Curves

It is safest to perform anterior release in a stiff curve to minimize the technical difficulty and risk of complication (loss of fixation) while attempting to correct a stiff deformity from a posterior approach alone. Posterior Osteotomies in combination with open anterior release. Some have advocated thoracoscopic anterior release. Anterior release may also be necessary in the case of severely stiff curves. The timing between anterior release and posterior instrumentation and fusion depends on the comorbidities of the patient. Alternatively, preoperative halofemoral traction has been reported to obviate the need for anterior surgery in stiff curves.²⁴



Figs. 103.17A to G: When passing Luque wires it is essential to roll the wires under the lamina (A to D) with extra caution taken not to catch the tip of the wire under the lamina, (E) placing the wire into the canal and ultimately place pressure on the spinal cord. (F and G) The wires are bent down the midline in the middle and the ends are bent flat down against the paraspinal muscles.

INTRAOPERATIVE AND POSTOPERATIVE CONSIDERATIONS AND COMPLICATIONS

Infection

The rate of infection after spinal deformity surgery in patients with neuromuscular disease contributes significantly to the morbidity of surgical intervention in this group of patients. Recently, a multicenter analysis of rates, risk factors, and pathogens following spinal instrumentation for scoliosis was done on 1,347 procedures performed in 946 patients. Procedures performed in patients with neuromuscular disease had the highest rate of infection at 9.2%.²⁵ Similarly, a retrospective review of 1,571 pediatric patients who had spinal deformity corrective surgery showed higher rates in patients with neuromuscular disease with the rates according to diagnosis being myelomeningocele 19.2%, cerebral palsy 11.2%, and myopathies 4.3%.²⁶ *Staphylococcus aureus*, *S. epidermidis*, and *Pseudomonas aeruginosa* were the most common organisms. Half of the patients required hardware removal to eradicate the infection and 41% of these patients had progression of their deformity. Others have cited enteric organisms such as *Escherichia coli*, *Enterococcus*, and *Proteus* as causative organisms later due to stool incontinence and concomitant urinary tract infection.^{27,28} Master and colleagues found that the presence of a ventriculoperitoneal (VP) shunt was a risk factor for infection.²⁹ At our own institution, we found that the two most significant associated factors with deep wound infection are the residual Cobb angle and the development of any postoperative wound breakdown. Other risk factors include malnutrition, allograft bone, increased blood transfusion, greater length of surgery, increased comorbidities, increased cognitive impairment, and urinary/stool incontinence.

Any measures taken to prevent postoperative infection are critical. Antibiotic prophylaxis should include coverage for *Staph aureus* and the surgeon should also consider coverage of methicillin-resistant *Staph aureus* (MRSA). Borkhuu and colleagues compared the risk of deep wound infection in a group of patients augmented by allograft mixed with gentamicin with a group augmented by allograft bone alone. The group with allograft mixed with gentamicin had an infection rate of 3.9% compared to 15.2% in the group with allograft bone alone. Currently, the senior author uses IV antibiotic prophylaxis with Ancef for patients with no comorbidities, and vancomycin or clindamycin in patients

with comorbidities, patients in chronic care facilities, and those colonized with MRSA. Liquid gentamicin (8–10 mg/kg body weight mixed with 30–60 cc of freeze dried allograft) is placed into the wound (Dias, 1996). A watertight closure of the wound is performed with a zero tolerance for any wound leakage. A surgical glue sealant system is used along with a moisture-protective bandage to prevent any stool or urine from contaminating the wound. If a wound infection does occur, an aggressive early irrigation is performed (multiple if necessary) with a vacuum-assisted closure of the wound and 6 weeks of IV antibiotics plus 6 months of suppressive per os or G-tube antibiotics are given as directed by the infectious disease specialists. Removal of hardware is done only in late or resistant infections (> 6 months).

Blood Loss

Jain and colleagues showed that cerebral palsy and other neuromuscular disorders had significantly higher normalized blood loss during spinal fusion than idiopathic scoliosis.³⁰ Brenn et al. stated that there is increased intraoperative blood loss that starts earlier in neuromuscular scoliosis compared to idiopathic scoliosis.³¹ While baseline prothrombin time and partial thromboplastin time were within normal range in neuromuscular scoliosis patients, they were still significantly different compared to that in idiopathic patients and by the time patients reached 15% blood loss, both were abnormal. The anesthesiologist and surgeon should be prepared for the possibility of major intraoperative blood loss. Increased bleeding was attributed to nutritional differences, altered tissue integrity, hepatic dysfunction, and the use of antiepileptic medications.

Type and cross-matched blood should be available up to twice the patient's blood volume as well as fresh frozen plasma and platelets. A cell saver machine is also helpful. In addition, core body temperature should be maintained at 37°C. Many patients are predisposed to hypothermia that increases bleeding. Antifibrinolytics may also have a role in reducing intraoperative bleeding.³²⁻³⁴

Currently, Amicar has been taken off the market leaving aprotinin and tranexamic acid for clinical use. Vitale and others have also shown some efficacy in the use of recombinant human erythropoietin in increasing hematocrit levels in children with neuromuscular disease undergoing scoliosis surgery.

Currently, our institution utilizes tranexamic acid in all patients with neuromuscular disease undergoing spinal deformity corrective surgery. Fresh frozen plasma and packed red blood cells are given early in the procedure.

Neurological Injury

Spinal cord monitoring should also be considered in patients who do standing transfers through ambulators.³⁵ The use of spinal cord monitoring is helpful in protecting lower extremity function when it is present. Using multiple recording sites of somatosensory spinal-evoked potentials and by administering motor-evoked potential procedures, it is possible to monitor spinal cord function in patients with neuromuscular disease, thus avoiding postoperative neurologic deficits.³⁶ While somatosensory cortical-evoked potentials are unreliable, somatosensory spinal-evoked potentials are possible to obtain in most cases used to detect sensory pathway integrity via testing the dorsal columns.³⁷ For those paralytic patients and myelomeningocele patients, it is not beneficial. Monitoring although possible during surgical correction of scoliosis due to cerebral palsy, it may be potentially unreliable.³⁸

Other neurological considerations include the postoperative evaluation of patients with pre-existing VP shunts to confirm the structural integrity of the shunt postoperatively compared to the preoperative evaluation (*see* Fig. 103.3). Symptoms of hydrocephalus may include headache, nausea, lethargy, cognitive changes, neurologic decline, or even death.

Cardiac

Cardiac arrest may occur from profound hypovolemia, hemo- or pneumothorax, air embolism, disseminated intravascular coagulation, or anaphylaxis due to latex. The surgeon should be especially mindful of hypotension during the corrective maneuver that can cause decreased venous return. We have also noted a decrease in intraoperative cortisol in many of the children with neuromuscular disease, especially those with upper motor neuron disease. In such case, cortisol is given intraoperatively to allow for an adequate stress response of the patient.

Respiratory

Postoperatively, frequent pulmonary toileting is necessary to prevent atelectasis and mucous plugging of major bronchi. Patients may be at risk for prolonged ventilator support postoperatively, especially if they have significant preoperative restrictive lung disease such as patients with muscular dystrophy and SMA.

Gastrointestinal

Postoperative ileus is common in patients with neuromuscular disease. Patients with G-tubes can begin feedings as soon as bowel sounds are heard. Gastrojejunostomy and nasojejunostomy tubes or hyperalimentation should be considered if regular feedings or oral intake is delayed much beyond 3–5 days. Pancreatic enzyme elevation and pancreatitis are common in patients with neuromuscular disease postoperatively.³⁹ Oral and gastrostomy feedings are avoided while pancreatic enzymes are elevated.

SPECIAL NEUROMUSCULAR DISEASE CONSIDERATIONS

Cerebral Palsy

The most prevalent neuromuscular disorder in most modernized cultures is cerebral palsy. It is a heterogeneous disorder that is caused by a static lesion to the immature motor cortex. The prevalence of scoliosis in the cerebral palsy population is proportional to the severity of neurologic impairment. It ranges from 5% in spastic diplegia to 64–74% in spastic quadriplegia. As scoliosis progresses, children who are dependent sitters with quadriplegic pattern involvement, initially demonstrate a postural scoliosis and kyphosis. In early and middle childhood, the spinal deformity is easily controlled with seating adjustments. In these early and middle stages of childhood, the structural element and flexibility of the scoliosis usually demonstrate little change. As the children enter into adolescence, however, particularly with the introduction of pubertal hormones and the adolescent growth spurt, the magnitude of the scoliosis increases dramatically, often at a rate of 2°–4° per month.^{1,2}

The magnitude of the scoliosis almost consistently increases to about 60°–90° range, which greatly affects sitting balance as well as head and arm control. Subsequently the stiffness of the structural curve follows thereafter roughly 6–12 months later. During this rapid increase in curve magnitude and stiffness, the family and caretakers commonly acknowledge the curve with increased problems in the child's head control, arm usage and upright sitting. The timeframe when the family and caretakers begin to notice and understand the problems caused by the scoliotic curve is approximately 2- to 3-years period whereby then the spinal deformity becomes fixed with minimal flexibility. Some children with severe quadriplegic pattern

involvement never develop scoliosis. For other individuals progression may be delayed into adulthood in patients with less neurologic deficit. In individuals who enter adulthood with mild scoliosis, the risk of continued progression is rather high. In one report, a curve $>40^\circ$ increased at a rate of 4° per year.⁴⁰ In adults with neuromuscular scoliotic curves over 40° , it has been recorded that progression continues to a mean of 80° .² Thometz and Simon, reported progression after skeletal maturity to be highest in lumbar and thoracolumbar curves $>40^\circ$. Other data suggest that curves as low as 20° at the end of growth may continue to advance at a rate of approximately 0.8° per year.¹

The scoliosis curve pattern in cerebral palsy can be classified by single versus double, and presence or absence of pelvic obliquity. Pelvic obliquity occurs secondary to the scoliotic deformity extending to the pelvis. Long C-shaped curves with pelvic obliquity generally occur in more severely involved nonambulatory patients with poor balance and righting reflex. Curves that are more S-shaped tend to occur in sitting or walking patients with better balance. Sagittal plane deformities are also a common problem, including lumbar hyperlordosis and thoracic hyperkyphosis. These deformities often cause discomfort and impair balanced sitting. Conservative treatment with seating modifications and bracing is temporary and does not halt progression of the spinal deformity. In younger children with flexible scoliosis, conservative management may allow the spine time to maximize growth while also temporarily assisting with upright sitting posture.

Surgical management for scoliosis is indicated in progressive curves over 60° when the child is not tolerating seating (in nonambulators) and standing (in ambulators). Surgery may also be indicated to alleviate pain or to correct pelvic obliquity prior to correcting a concomitant hip dislocation. Surgical correction of scoliosis and hyperkyphosis/hyperlordosis involves posterior spinal fusion with instrumentation usually from T1 or T2 down to the sacrum to prevent adding on above or below the fusion. Occasionally, fusion to the pelvis can be avoided in very good ambulators with excellent standing balance. These patients usually have more of an idiopathic curve pattern (double curve) indicating that they are able to “right” their head over the center of the sacrum through the development of a compensatory curve.

Myelomeningocele

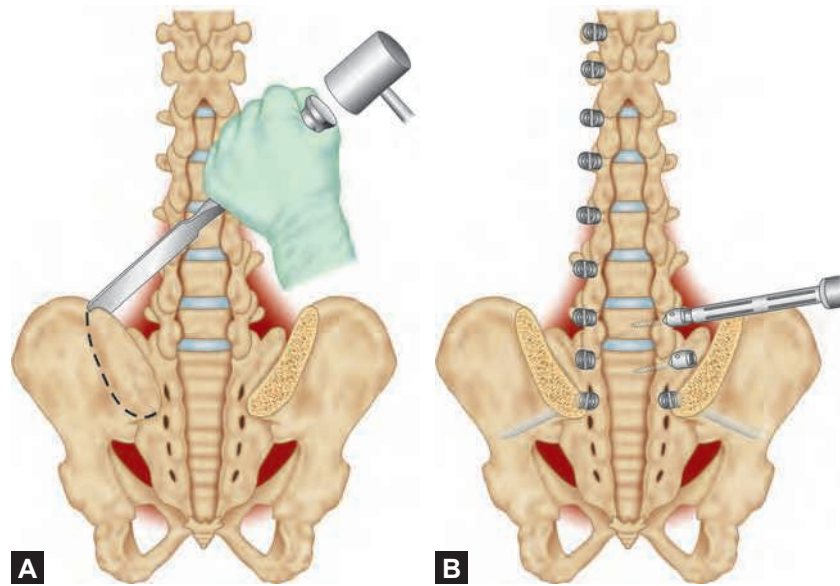
This condition is a congenital malformation of the nervous system due to a neural tube defect of neuroectodermal

cells early in embryonic development leading to a varied spectrum of motor and sensory deficits. This congenital malformation has been associated with maternal hyperthermia and folate deficiency. Surgical repair of myelomeningocele may pose life-threatening complications with 24.4% of these children having associated scoliosis.⁴¹ Neurologic deterioration may occur at any age due to hydrocephaly, hydrosyringomyelia, Arnold–Chiari deformity, and tethered cord syndrome. Chronic skin ulceration and impaired pulmonary function often occur due to increasing spinal deformity. If scoliotic onset is sudden and associated with acute neurologic symptoms, one should suspect associated conditions of hydromyelia and tethered cord syndrome.

The level of spinal cord defect impacts the child’s clinical presentation, with generally the higher the level of defect, the greater the prevalence of spinal deformity. A long C-shaped curve is associated with a high level of paralysis and typically occurs at a young age. Those children in whom the last intact laminar arch was in the thoracic region developed scoliosis 89%, in upper lumbar levels 44%, and in lower lumbar levels 12%.⁴² Often the spinal curvature is a consequence of congenital deformity prompting hyperkyphosis and muscle imbalance distal to that segment malformation involving the trunk hip. Typically scoliotic curves $<40^\circ$ – 50° can be managed nonoperatively. Severe sagittal deformity, as well as hip contractures, can prevent sitting and comfortable positioning. Custom molded wheelchairs and sitting supports can offer temporizing upright positioning. Bracing younger children may also assist with comfort in sitting; however, bracing will not prevent eventual spinal deformity progression. Surgical intervention of significant hip contractures, which can worsen lumbar lordosis and scoliosis deformities, should be addressed before considering spinal surgery.

Surgical treatment can be uniquely challenging in this population due to the severe multiplanar spinal deformities, the presence of congenital vertebral malformations, absence of posterior elements, abnormal pedicle anatomy, truncal obesity, and compromised skin integrity. Preoperative considerations include the presence of shunts for hydrocephalus, Arnold–Chiari malformation, tethered cord, bladder augmentation procedures, bowel incontinence, thoracic insufficiency syndrome, and marked contractures of the lower extremity.

Preoperative CT scan and if possible intraoperative C-arm or O-arm navigation are helpful in the placement of pedicle screw that is often necessary due to the frequent



Figs. 103.18A and B: (A and B) Pedicle screw placement into the lower lumbar vertebral bodies and sacral promontory can be better obtained after completing osteotomies of the iliac wings.

absence of the posterior elements. Careful planning of skin incisions away from pre-existing scarring should be performed. The medial portal, S2 iliac pelvic screw placement is especially helpful in these patients as it avoids screw prominence. The combination of truncal obesity, combined with increased lumbar lordosis may make it difficult to cannulate pedicles that are very laterally positioned. Osteotomy of the iliac wings is helpful to allow better pedicle cannulation and trajectory of the pedicle screw placement (Figs. 103.18A and B). Postoperative wound management is important. Skin closure can be challenging and the assistance of the plastic surgeon to close the skin can be extremely helpful in case there is a need to mobilize skin and/or muscle flaps to gain closure. Low pressure mattresses should also be considered postoperatively (Figs. 103.19A to F).

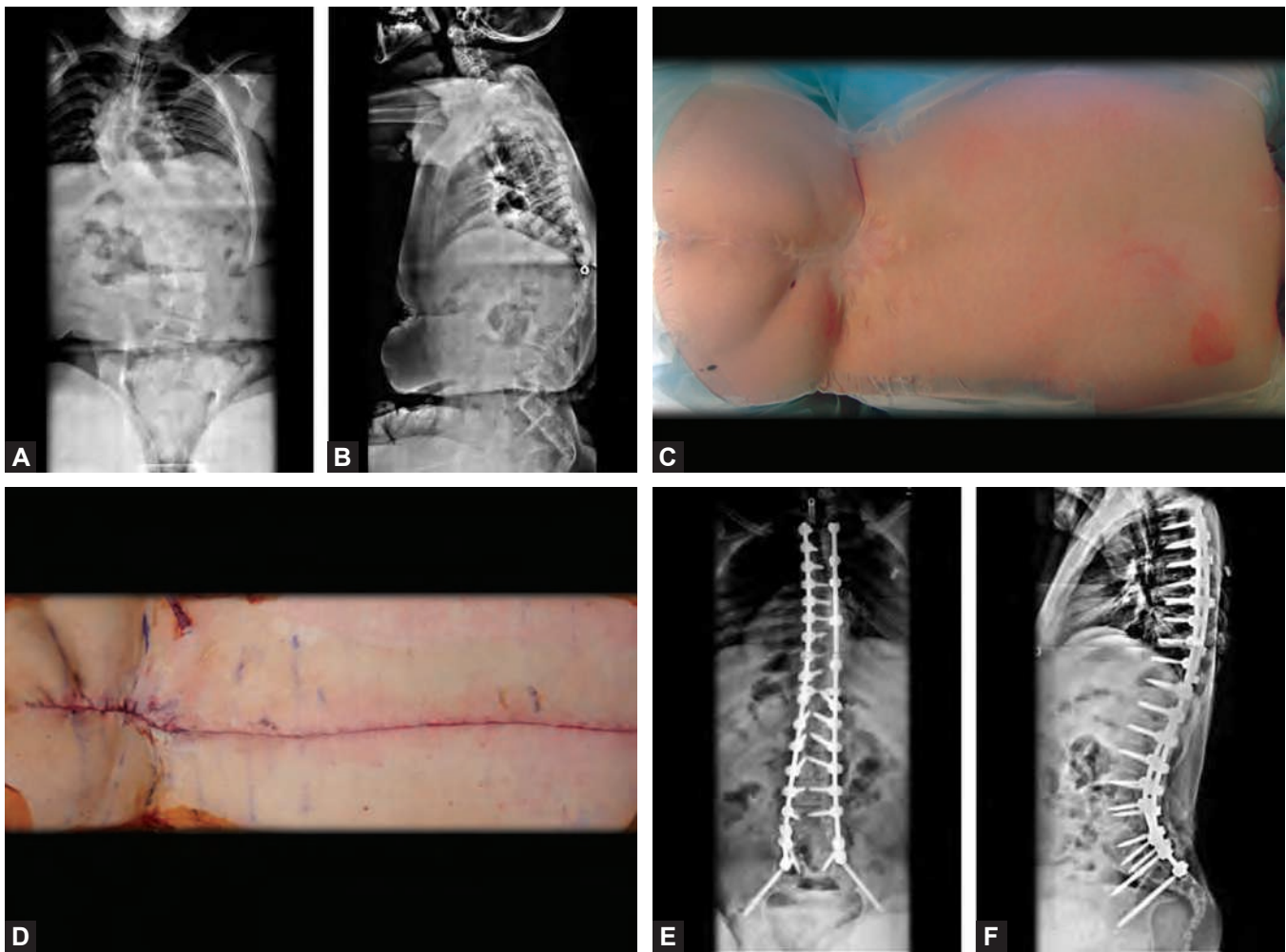
Spinal Muscular Atrophy

This disorder is an autosomal recessive disease with two genes on the chromosome 5q locus of the survival motor neuron gene and neuronal apoptosis inhibitory gene. The result is diminished abundance of the protein resulting in death of neuronal cells in the anterior horn of the spinal cord and subsequent system-wide muscle atrophy.⁴³ There is a slow progression of weakness without sensory impairment caused by disease of motor neurons in the spinal cord and brainstem. Patients tend to deteriorate over

time; however, prognosis varies with SMA type and a great degree of individual variability. Recurrent respiratory problems are the primary cause of morbidity.

Four forms of the disease exist: type 1 infantile (Werdnig-Hoffmann, onset age 0–6 months), type 2 intermediate (Dubowitz, 6–8 months), type 3 juvenile (Kugelberg-Welander, >18 months), and type 4 adulthood (sometimes a subset of type 2).⁴⁴ Most children with early disease die at a young age and thereby have no spinal treatment. Those children with intermediate and juvenile types who grow into adolescence develop progressive spinal deformity, with most often the curve beginning in the first decade. Scoliosis tends to progress 8° per year, and when children become nonambulatory the curve progression occurs at 3° per year.⁴⁵ The most common curves are thoracolumbar and single thoracic patterns, with a third of patients having an associated kyphosis deformity. Even though these curves are of large magnitude, they often are flexible. Prevention of curve progression is not affected by bracing; however, in younger patients may allow further spine growth until surgical fusion is necessary.⁴⁶

Posterior stabilization should extend from T3 to the sacropelvis. In some patients, the pelvis can be rather small, with abnormal anatomy and poor bone quality leading to challenging pelvic fixation. In patients with excessive lordosis distal rod fixation as well can be difficult. Pelvic fixation into the iliac crest or S2 screw insertion can be useful in these situations. In the early postoperative



Figs. 103.19A to F: Preoperative and postoperative radiographs and clinical pictures of a nonambulatory patient with mid-lumbar level myelomeningocele progressive kyphoscoliosis.

period, the major complications are related to atelectasis, pneumonia, and respiratory function. Decline in percentage predicted force vital capacity in patients with SMA type 2 and 3 was 7.7% per year preoperatively and reduced to 3.8% after spinal corrective surgery.⁴⁷ Due to progressive neuromuscular weakness of the disease, pulmonary function continues to regress. After spinal stabilization even though pulmonary function declines, a straight spine positioned over a level pelvis provides upright sitting, better upper extremity function, and improved quality of life and caretaking.

Muscular Dystrophy

This condition is a group of muscle diseases that weaken the musculoskeletal system characterized by progressive

skeletal muscle weakness, defects in muscle proteins, and the death of muscle cells and tissue.⁴⁸ Predominantly these conditions are inherited; however, mutations of the dystrophin gene and nutritional defects at the prenatal stage are also possible. Dystrophin protein is found in the muscle fiber membrane and often there is a loss of muscle mass that may be difficult to appreciate as some types of muscular dystrophy cause a pseudohypertrophy due to fat and connective tissue build up. These muscle diseases include Becker's muscular dystrophy, congenital muscular dystrophy, Duchenne muscular dystrophy, facioscapulo-humeral muscular dystrophy, distal muscular dystrophy, Emery-Dreifuss muscular dystrophy, limb-girdle muscular dystrophy, myotonic muscular dystrophy, and oculopharyngeal muscular dystrophy.

Duchenne muscular dystrophy is a sex-linked recessive condition involving a defect on the Xp21.2 locus on the X chromosome leading to a marked decrease or absence of the protein dystrophin.⁴⁹ Death usually occurs in the second or third decade resulting from pulmonary or cardiac failure. Children become progressively weaker as they advance in age and eventually become nonambulatory. Scoliosis affects 90–100% of patients who do not ambulate.^{50,51} One study suggests that in nonambulatory children scoliosis was absent in 10% and mild or $>30^\circ$ in 13%.⁵⁰ Modalities of bracing, lordotic positioning, and wheelchair modification may delay but will not prevent spinal deformity. Steroid therapy has been shown to slow progression of weakness, allow longer ambulation, and reduce the progressive scoliosis.

Curve progression correlates strongly with a decline in respiratory function, and early surgery has the advantage of preserving cardiopulmonary function. Even though patients with Duchenne muscular dystrophy have progressive, restrictive lung disease, the lung function is related to curve magnitude. In general, surgical intervention should be undertaken once the curve reaches 35° before critical respiratory decline occurs. Peak progression of scoliosis occurs between 13 and 15 years of age at 1° – 3° per month. Posterior spinal fusion for scoliosis is associated with a significant decrease in the rate of respiratory decline.⁵²

Typically fusion includes high-thoracic level of T2 or T3 to L5 or S1 and has similar results in the apex of the curve that is above L1, and if the scoliosis is $<40^\circ$ with pelvic obliquity $<10^\circ$, then fusion to L5 is sufficient. If apex of the deformity is below L1, fusion should extend to the pelvis.⁵³ Operative fixation has been shown to be successful with posterior-only pedicle screw fixation achieving balanced sitting posture and maintenance of deformity correction.^{54,55} Instrumentation with Luque system Galveston pelvic fixation and sublaminar wires, two rods with cross-links, or a unit rod have proven stable. Other options included using segmental fixation with all pedicle screws or combination of wire and pedicle screw fixation. Postoperatively the major complications are related to blood loss and pulmonary problems. All fixation options fulfill the crucial goals to permit immediate immobilization postoperatively, maintain upright sitting balance, and maximize comfortable function.

Spinal Cord Paralysis

Spinal cord injury is an insult to the spinal cord resulting in a change, either temporary or permanent, in the cord's

normal motor, sensory, or autonomic function. Depending on where the spinal cord and nerve roots are damaged, the symptoms can vary widely, from pain to paralysis. Regarding the mechanism of injury, there appeared to be two distinct mechanisms that affected younger children and adolescents. Motor vehicle accidents typically affect younger children, whereas adolescents are frequently injured during sporting activities.⁵⁶

One study examined children who sustained spinal cord injuries between birth and age 21 years to review the rate of scoliosis progression. Patients who sustained injury before the adolescent growth spurt had 97% development of spinal deformity, whereas those after adolescent growth had 52%.⁵⁷ Because of these differences, traumatic spinal cord injury should be highly suspected in the presence of abnormal neurological examination, a high-risk mechanism of injury, or a distracting injury, even in the absence of abnormalities on plain radiographs. The predominant curvature type is that of a long C-shaped curve. Bracing may be effective in small curves $<20^\circ$; however, it is neither demonstrated where bracing is effective at preventing curve progressing in those deformities $>20^\circ$ nor delay the time to corrective surgery.⁵⁸

The preoperative considerations that are specific to children with spinal cord injury include assessment for the presence of potential urinary tract infections, evaluation for deep venous thrombosis (DVT) with ultrasound of all four extremities,⁵⁹ and ensuring a bowel “clean out” the day before surgery. Most of these patients require long fusions from T1 to T2 down to the pelvis. Of special note, however is that these patients rely on an increased kyphosis to perform activities of daily living such as self-catheterization. The anesthesiologist should avoid giving succinylcholine that may cause sudden cardiac arrest.⁶⁰ When performing surgery, the surgeon must keep this in mind and should consider observing patient for a period of time in a temporary TLSO to preoperatively plan the optimum sagittal profile to fuse the patient in. The lateral profile of the rods can be prebent to match the lateral radiographs. Usually the final sagittal profile of the fusion provides for some kyphosis. Postoperatively, prophylaxis for DVT should be considered.

Rett Syndrome

Rett syndrome is an X-linked disorder. Some children have a mutation on the MECP2 gene. It affects females almost exclusively. Childhood development is normal until 6–18

months of age at which time a rapid deterioration in cognitive and motor function occurs. The majority of these children have a seizure disorder. The neurological picture may become relatively static for many years after the initial deterioration. Clinically, the spectrum of motor involvement is variable with some children remaining ambulatory and others becoming wheelchair-bound. Rett syndrome is often mistaken for cerebral palsy. Scoliosis is reported in up to 80% of patients. Long C-shaped curves are common. Younger children presenting with scoliosis have a higher progression rate. Bracing is usually ineffective in preventing curve progression. Surgical fixation is similar to that of the cerebral palsy patient with screw fixation to the pelvis and sublaminar fixation up to T1 or T2. Surgical treatment in Rett syndrome after spinal fusion provides successful correction and restoration of sitting balance. Larsson and colleagues prospectively followed 23 consecutive girls after spinal fusion and assessed sitting balance, number of seating supports, weight distribution, time used for rest, and Cobb angle, all improved after surgery.⁶¹

OUTCOMES

In general, the goals of spinal surgery in patients with neuromuscular disorders are to enhance quality of life by improving balanced sitting and posture, improving pulmonary and gastrointestinal function, and reducing pain and deformity. However, neuromuscular surgery is rather challenging. In a large multicenter study reviewing cases of pediatric scoliosis, neuromuscular scoliosis had 17.9% complications.⁶² In our series of 107 patients, complications included 14 deep infections, 3 deaths, 15 cases of prominent hardware, and 1 pseudarthrosis.¹⁰ The primary instrumentation for treatment of neuromuscular scoliosis is the unit rod instrumentation. It is simple to use, considerably less expensive than most systems, associated with low complication and reoperation rates, and achieves successful long-term correction 70–80% of the preoperative curvature magnitude and 80–90% correction of pelvic obliquity.^{7,20} In ambulatory patients with cerebral palsy who had posterior spinal fusion using unit rod instrumentation all of 24 patients maintained ambulatory status postoperatively.⁶³ Sagittal plan deformity has also been effectively corrected using the unit rod in patients with hyperlordosis and kyphosis.⁴

Neuromuscular scoliosis is associated with increased hospital stay and risk of complications. Nonambulatory status preoperatively and curve magnitude of $\geq 60^\circ$ were

directly associated with increased risk of major complications and indirectly associated with increased length of hospital stay.²⁹ Progressive pulmonary disease typically seen in patients with neuromuscular disease often is related postoperatively to development of pulmonary complications. Those patients with neuromuscular disease with a preoperative force vital capacity of $<39.5\%$ of predicted value, forced expired volume of $<40\%$, cob angle $>69^\circ$, or age >16.5 years were found to have increased likelihood to have postoperative pulmonary complication.⁶⁴

Important aspects of postoperative assessment include overall function, appearance, ease of care, and improved quality of life. Outcome measures should differentiate treatment effects from underlying disease functional impairments.⁶⁵ Some might question whether spinal deformity corrective surgery is truly beneficial for patients with neuromuscular disease, particularly those most severely involved. In one survey of 190 parents and caretakers assessed for functional improvement in children with cerebral palsy after spinal fusion, 95.8% of parents and 84.3% of caretakers would recommend spinal surgery again.⁶⁶ Multiple reviews report caretakers, families, and patients with severely involved neuromuscular diseases are most often satisfied with the surgical correction, improved appearance, and enriched quality of life.⁶⁷⁻⁷⁰

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Nonoperative Treatment of Adolescent Idiopathic Scoliosis

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Snapshot

- » Argument for Observation
- » Bracing
- » Physical Therapy
- » Other Treatment Modalities

INTRODUCTION

Goals of Treatment

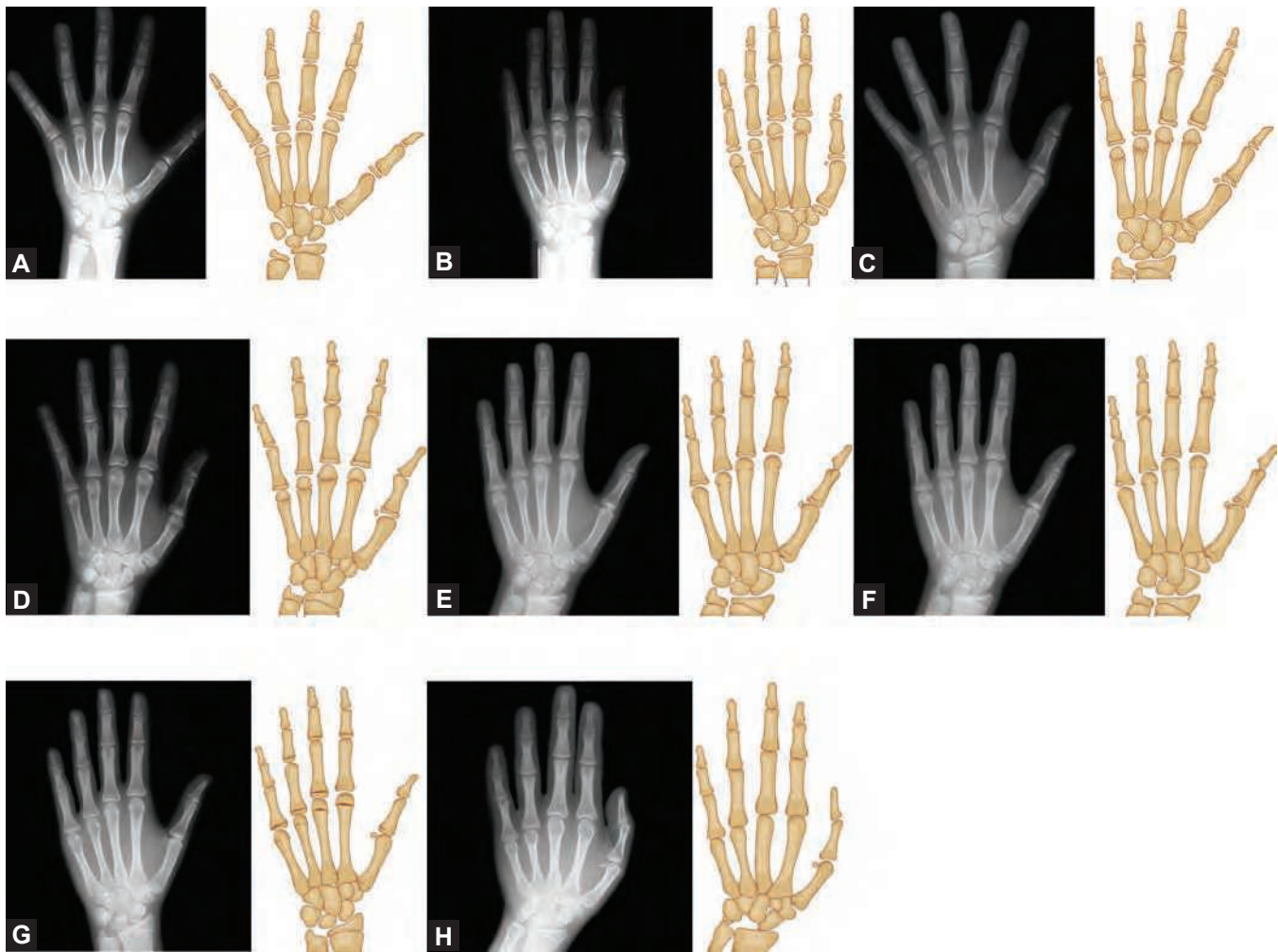
Adolescent idiopathic scoliosis (AIS) is a three-dimensional deformity of the spine, affecting 1–3% of children in the at-risk population of children between the ages of 10 and 16 years.¹ The prevalence of AIS diminishes as curve size increases; the prevalence of curves above 20° is 0.3–0.5% and for curves over 30° this drops to 0.2–0.3%.² While AIS can progress rapidly during growth, this disease process rarely has effects that are so dramatic that immediate surgery is necessary. Nonetheless, scoliosis that develops during adolescence can affect patients during their youth and throughout later stages in life. In fact, the effects of AIS can manifest much later in life after the spinal curvature surpasses a critical threshold, and beyond this point there is increased risk of further progression and health problems such as pain, torso deformity, psychological disturbance, and pulmonary dysfunction.³

While advocates of early surgery emphasize the benefits of surgical deformity correction with regard to physical and psychological outcome, opponents base their arguments on the risk of complications and the fact that despite encouraging results with short and intermediate follow-up, the subjective long-term outcomes are yet to be fully elucidated.⁴ The goal of nonoperative treatment is to decrease the need for surgical intervention by

reversing, arresting, or slowing the curve progression thereby preventing undesirable outcomes in adulthood. Nonoperative treatments for AIS include observation, bracing, physical therapy, and other novel therapeutics.

Assessment of the AIS Patient

When assessing patients with AIS, it is important to identify those patients who are at greatest risk of progression to a larger curve. Larger Cobb angles and skeletal immaturity have long been identified as key clinical predictors of curve progression.⁵ A thorough history will reveal other potential risk factors for progression, including a family history of scoliosis. On physical examination, appearance and overall balance of the patient should be assessed. Tanner staging can help indicate the developmental maturity of the child (Figs. 104.1A to H). A paraspinal prominence may be detected on Adams forward bending test and may be further evaluated with a scoliometer, which is a tool used to measure the degree of spinal deformity while bending forward. A detailed neurological examination should be performed to provide a baseline assessment and to look for possible deficits. Radiographs are necessary in order to assess the coronal and sagittal degree of the curve, as well as the curve pattern and rate of curve progression over time. The Risser Sign, a quantification of iliac apophysis ossification, has long been an important indicator of skeletal maturity and is associated with risk of curve progression



Figs. 104.1A to H: Tanner staging: (A) **Stage 1:** The key finding in stage 1 is that all of the digital epiphyses are not covered. In this case, the patient is at the end of stage 1. Particularly noticeable at the third middle phalanx, the epiphysis is not as wide as the metaphysis. More often, this finding is most noticeable on the fifth middle phalanx and metacarpal head. (B) **Stage 2:** The key finding in stage 2 is that all of the digital epiphyses are covered. In this case, the patient is near the end of stage 2. The epiphyses are now all as wide as their metaphyses (covered). The dorsal and palmar surfaces of the metacarpal heads are clearly delineated. There is some capping of the second through fifth proximal phalanges but nowhere else. (C) **Stage 3:** The key finding in stage 3 is that the preponderance of the epiphyses cap their metaphyses. The capping is a small bend over the metaphyseal edge. In the metacarpals, the second through fifth heads are wider than the metaphyses. The epiphyses cap the thumb metacarpal and all of the digits. (D) **Stage 4:** The key feature of stage 4 is the beginning of distal phalangeal physal closure. In this case, the distal phalangeal physis of the thumb appears closed on the radiograph, but its rotation makes it more difficult to see than the other digits. The distal phalangeal physes of the second through fifth digits are beginning to close. Physal closure starts in the center of the physis. The remainder of the digits are fully capped, and the metacarpal heads are wider than their metaphyses as in stage 3. (E) **Stage 5:** The key feature of stage 5 is that all of the distal phalangeal physes are closed. If there is any black (growth cartilage) rather than white (physal scar) in the physis, the radiograph remains as stage 4. The remainder of the epiphyses are capped, and the metacarpal heads are wider than the metaphyses (see stage 3 as demonstrated in Table 104.1). (F) **Stage 6:** The key feature of stage 6 is that some of the proximal or middle phalangeal physes are closing. In this stage, all of the distal phalangeal physes are closed and some of the proximal and middle phalangeal physes are closing. The second through fifth metacarpal physes typically stay open longer than those of the other small bones. When the metacarpal physes go from black (physis) to white (physal scar), then the physis is considered "closed" or "fused" for this staging system. (G) **Stage 7:** The key feature of stage 7 is that all of the physes, except for those of the distal parts of the radius and ulna, are closed. There are no black physal lines remaining for any digits or metacarpals. Stage 7 ends when the distal radial and ulnar physes are white (physal scar) rather than black (persistent physis). (H) **Stage 8:** The key finding of stage 8 is closure of all physes. The residual physal lines may appear white, but there are no black physal lines. *Source:* Available from <http://health-7.com/Atlas%20of%20Pediatric%20Physical%20Diagnosis/Tanner%20Staging/1>.



Fig. 104.2: Risser sign.
 Source: Available from http://www.srs.org/professionals/conditions_and_treatment/adolescent_idiopathic_scoliosis/treatment.htm

(Fig. 104.2).⁵ More recently, the Sanders-described Simplified Tanner-Whitehouse Scale (“Sanders stage,” for short), using hand radiographs, has proven to be another useful prognostic indicator of progression.⁶ Sanders staging allows for the assessment of skeletal maturity based on ossification of the digital epiphyses, phalangeal physes, and radial physis. The greatest utility of Sanders staging is its ability to quantify maturity within Risser stage 0—the level of maturity most associated with risk of progression.

The correlation of the Sanders stage with the curve acceleration phase was 0.91 (Table 104.1). While it is not routine, pulmonary function testing may also be used as a tool in patients who exhibit or complain of pulmonary symptoms. The literature has demonstrated that pulmonary function may be negatively impacted in patients with AIS, although the clinical implication of this impact in patients with nonsurgical curves has not been fully elucidated.^{7,8}

Table 104.1: The simplified Tanner-Whitehouse-III system vs. other maturity assessments.

Stage	Key features	Tanner-Whitehouse-III stage	Greulich and Pyle reference	Related maturity signs
1. Juvenile slow	Digital epiphyses are not covered	Some digits are at stage E or less	Female 8 yr + 10 mo, male 12 yr + 6 mo (note fifth middle phalanx)	Tanner stage 1
2. Preadolescent slow	All digital epiphyses are covered	All digits are at stage F	Female 10 yr, male 13 yr	Tanner stage 2, starting growth spurt
3. Adolescent rapid—early	The preponderance of digits are capped. The second through fifth metacarpal epiphyses are wider than their metaphyses.	All digits are at stage G	Female 11 and 12 yr, male 13 yr + 6 mo and 14 yr	Peak height velocity, Risser stage 0, open pelvic triradiate cartilage
4. Adolescent rapid—late	Any of distal phalangeal physes are clearly beginning to close (see detailed description in the text)	Any distal phalanges are at stage H.	Female 13 yr (digits 2, 3, and 4), male 15 yr (digits 4 and 5)	Girls typically in Tanner stage 3, Risser stage 0, open triradiate cartilage
5. Adolescent steady—early	All distal phalangeal physes are closed. Others are open.	All distal phalanges and thumb metacarpal are at stage I. Others remain at stage G.	Female 13 yr + 6 mo, male 15 yr + 6 mo	Risser stage 0, triradiate cartilage closed, menarche only occasionally starts earlier than this
6. Adolescent steady—late	Middle or proximal phalangeal physes are closing	Middle or proximal phalanges are at stages H and I	Female 14 yr, male 16 yr (late)	Risser sign positive (stage 1 more)
7. Early mature	Only distal radial physis is open. Metacarpal physeal scars may be present	All digits are at stage I. The distal radial physis is at stage G or H	Female 15 yr, male 17 yr	Risser stage 4
8. Mature	Distal radial physis is completely closed	All digits are at stage I	Female 17 yr, male 19 yr	Risser stage 5

Table 104.2: Elements of evaluation for AIS.

History	Family history
	Medical history
	Developmental history
	Neurologic symptoms
Physical examination	Coronal/Sagittal balance
	Neurologic examination
	Reflexes (DTR, Babinski, umbilical)
	Strength/Sensation
	Coordination
	Gait
	Skin abnormalities (i.e. café au lait spots)
	Adams forward bending test
	Scoliometer
	Tanner stage
Radiographic evaluation	Standing long cassette scoliosis film
	Cobb angle (coronal plane)
	Kyphosis/lordosis (sagittal plane)
	Risser sign
	Hand film
	Bone age
	Simplified Tanner-Whitehouse stage
	MRI (If positive neurofindings or atypical curve pattern)

(AIS: Adolescent idiopathic scoliosis; DTR: Deep tendon reflexes; MRI: Magnetic resonance imaging).

Scoliscore, a prognostic genetic test that became available in 2009, uses a saliva sample to test 52 genetic markers associated with curve progression (Table 104.1). There is an algorithm based on this assay and the size of the curve at the time of diagnosis that creates a score between 1 and 200. This score indicates risk of curve progression to $>40^\circ$. While this test has been validated by its manufacturer, its clinical utility is dubious.^{9,10} Some propose that the test may be most useful in further stratifying patients with high-clinical risk of progression (i.e. Risser 0–1 and Cobb angle $>20^\circ$) in order to reduce unnecessary bracing and radiographic testing¹⁰ (Table 104.2).

ARGUMENT FOR OBSERVATION

The nonoperative treatment of AIS consists of observation, bracing, physical therapy, and other novel therapies. A central issue of debate pertaining to these treatments is whether bracing actually achieves what it purports to do, i.e. halts curve progression by unloading biomechanical stress on the spine. Between 1970 and 2012 the topic remained moot due to a general dearth of quality evidence to support bracing versus observation. Studies with

wide methodological variability, various biases, and, in many cases, a lack of control subjects all contributed to a clouded picture of the efficacy of bracing.¹¹ This has led many to advocate for “watchful waiting,” and has spurred debate regarding the effectiveness of regular screening for scoliosis in schools. In 2004, the US Preventative Services Task Force recommended against routine screening for asymptomatic AIS. However, a joint position statement from the American Academy of Orthopaedic Surgeons (AAOS), Scoliosis Research Society (SRS), Pediatric Orthopaedic Society of North America (POSNA), and American Academy of Pediatrics (AAP), citing a lack of evidence in the current literature, did not recommend against scoliosis screening and stated that if screening were to take place it should be performed twice for females at ages 10 and 12 years, and once for males at age 13–14 years.¹² Others have advocated strongly for observation noting that late-onset idiopathic curves rarely lead to organ failure, compromised future health, or social stigma; and in some cases, the decision to operate might be for purely cosmetic reasons.^{13,14} One retrospective review of 153 patients treated at a single institution with a policy of recommending against bracing for AIS found that, when the rate of surgical correction is used as the primary outcome, there was no advantage to bracing over observation.¹⁵

A second issue for consideration in the discussion of bracing versus observation is the potential risk to the child. Apart from pressure sores and discomfort, no major physical risks for bracing have been reported, though there is some literature examining the effect of bracing on mental and social health. In the practice of prescribing scoliosis braces it is common to encounter patients who's self image, psychosocial health, and quality of life (QOL) appear to suffer. However, several studies examining the effect of bracing on QOL have been conducted with the predominance of the evidence supporting the notion that bracing does not have a significant negative impact on self-image or QOL in AIS.^{16–19} Moreover, at long-term follow-up, AIS patients who were braced or observed reported QOL scores that did not differ from the population norms.²⁰

The multicenter prospective cohort study by Nachemson and Peterson, widely cited^{13,15,23} and considered to be some of the highest quality evidence to investigate bracing versus observation, studied 240 female subjects with AIS assigned to bracing, observation, or electrical stimulation. This study found that 36% of braced patients versus 66% of observed patients failed treatment (defined as $>6^\circ$ of progression).²¹ However, a 2007 literature review

by Dolan and Weinstein that pooled data from 18 studies regarding the need for eventual surgical intervention found no clear difference between braced or observed patients, though it did acknowledge several potential confounders including the heterogeneity of inclusion criteria used in studies, vague surgical indications, and the limited number of observed patients (only 139 observed subjects from three studies were included).²² The calls for a trial similar in scope and design to Nachemson and Peterson's original 1996 prospective study have not gone unheard—the results of Bracing in Adolescent Idiopathic Scoliosis Trial (BrAIST), a randomized, multicenter trial comparing observation to 18 hours of daily brace wearing, were published in the *New England Journal of medicine* in 2013. An analysis including both the randomized and preference cohorts (patients who chose bracing over observation), showed a rate of treatment success of 72% after bracing, as compared with 48% after observation. BrAIST concluded that bracing “significantly decreased the progression of high-risk curves to the threshold for surgery in patients with adolescent idiopathic scoliosis” and that “the benefit increased with longer hours of brace wear.”²⁴ Despite the strong conclusions in BrAIST, bracing treatment should be prescribed judiciously, taking into account Society on Scoliosis Orthopaedic and Rehabilitation Treatment (SOSORT) and SRS bracing criteria, access to the appropriate clinical resources, and, of course, the patient's overall clinical picture. Further consideration of bracing options and indications will be discussed later in the chapter.

■ BRACING

A Brief History of Bracing

The long and varied history of nonoperative attempts to correct spinal deformity begins in the 5th century BC with Hippocrates' attempts to apply axial distraction with an extension apparatus—the scamnum. Galen proposed adding direct pressure to the spine through use of binders and jackets in combination with Hippocrates' traction, and was a proponent of exercises thought to strengthen the chest wall musculature in an attempt to achieve distraction indirectly.^{25,26} A series of French efforts, beginning in the early 16th century with Paré's advocacy for iron corsets to be applied at 3-month intervals during the post-pubescent growth spurt was followed by Nicholas Andre's mid-eighteenth century theory that the development of scoliosis was purely postural and could be remedied through use of bracing or corsets and proper chair construction—a precocious attempt at ergonomic design.²⁶

Jean-Andre Venel, a Swiss orthopedist, used traction beds and bracing techniques at his hospital dedicated to the treatment of childhood skeletal deformities. A century later in the 1880s, Lewis Sayre applied plaster of Paris casts to patients' torsos—the “Sayre jacket”—while holding them in overhead traction, was merely an adjunct to the “gymnastic exercises” that he felt were necessary to strengthen the musculature at the convexity of the curve and inevitably improve sagittal balance.^{27,28} 1924 saw the advent of Lovett and Brewster's “turnbuckle” cast consisting of two sections of plaster cast hinged at the concavity with a screw that served to apply distraction to the convexity of the curve. It was recommended for full-time use, though the device was cumbersome, excessively restrictive, and merely applied a bending force without traction in light of the observation that bending a curve—as opposed to pulling on it, or applying traction—is a much more effective means of straightening it.²⁸ This theory, though slightly modified as a result of a more developed understanding of biomechanics, would surface again in the development of nocturnal bracing in the late 20th century.

Medical management and understanding of scoliosis remained fairly rudimentary until Roentgen's Nobel prize-winning introduction of the X-ray to medical science in 1895.³³ Rapid advancements in the technology over the next several decades led to relatively high-quality spinal films by the 1930s, and, for the first time, an appreciation of the three-dimensional nature of the scoliotic deformity. At the same time that the X-ray was developing, the increased incidence of tuberculosis and poliomyelitis led to a spike in spinal deformity, and the new surgical techniques developed by Hibbs, Risser, and Ferguson to treat the sequelae of Pott's disease and Polio were later applied to patients with idiopathic scoliosis.²⁶ Still, Risser's method, in which preoperative traction and casting held surgical candidates immobilized for up to a year prior to surgery and 8–10 months afterward in the “Risser immobilizer” (a modified turnbuckle cast that utilized an external frame to apply traction to the curve while also addressing the rotational deformity), gave a nod to the use of bracing in correction of spinal deformity.²⁸ Ponseti and Friedman's retrospective report of 117 fusions at 3-year follow-up noted that of the 100 cases attempting adjunctive correction with a “Risser jacket,” 81 achieved a preoperative correction of at least 20°. This work, which also attempted to classify outcomes based on the severity of the curve, its location, and its etiology, set the stage for the development of treatment guidelines for both surgical and nonoperative treatment of

scoliosis.²⁹ With the development of both devices and bracing techniques spurred on by their use in the surgical treatment of scoliosis, bracing for scoliosis as the primary intervention became an attractive and viable option.

Brace Types

Milwaukee Brace

First developed in 1946 by Blount and Schmidt for the postoperative adjunctive treatment of scoliosis secondary to poliomyelitis, the use of the Milwaukee brace for the nonoperative treatment of scoliosis gained popularity after the 1958 publication of their experiences with the brace in chronic and postoperative poliomyelitis and as a means of preventing the rapid progression of the curve at the end of the growth period.³⁰ Termed a cervicothoracolumbosacral orthosis, the Milwaukee brace applies traction to the spinal deformity through use of a steel and leather pelvic base from which one anterior and two posterior arms extend to support the head at the occiput and throat (Fig. 104.3). Derotational forces are applied at rib prominences through pads attached to the pelvic girdle or support arms. This class of brace has historically been used for higher thoracic and cervicothoracic curves, because thoracolumbosacral orthoses (TLSO), such as the Boston brace, fail to apply corrective forces to curves with an apex higher than T7–T8.

Wilmington Brace

Developed in 1969 at the request of a patient who refused both the Milwaukee and Risser braces, the Wilmington



Fig. 104.3: Milwaukee brace.

brace is the first significant and successful low-profile TLSO.²⁸ Its construction involves creation of a plaster cast of the patient's torso while applying traction and hand pressure to achieve the desired correction to the longitudinal and transverse deformities. The plaster cast is then used to fashion a model of the patient's torso on which the full-contact plastic jacket is modeled. Radiographs taken prior to removal of the initial plaster cast as well as after the brace has been fitted to the patient ensure that the desired curve correction and balance are achieved.³¹

Boston Brace (Figs. 104.4A and B)

The Boston brace is a TLSO similar to the Wilmington brace in both theory and design; however, the Boston avoids the



Figs. 104.4A and B: Boston brace for (A) thoracic curves (B) thoracolumbar curves.

difficulties associated with the molding process necessary for creation of the Wilmington brace by utilizing a modular system consisting of prefabricated components of varying sizes. The three basic brace types (lumbar, thoracolumbar, and thoracic) are designed for correction of curves with apices at spinal levels as high as T7, while various extensions (e.g. a modification to correct hypokyphosis) and additional padding allow for custom modification of the individual modules and application of corrective forces where necessary. In addition to applying forces that passively correct the curve (i.e. pads located at the curve apex or just below it), the standard model applies mild lumbar flexion and areas of relief opposite each area of force to promote curve correction as the patient actively pulls away from pressure zones. The brace also addresses rotational deformity through application of coupled rotational forces in the same rotational direction.

The Boston brace has gained popularity as an alternative to the Wilmington brace due to its low profile, ease of application, and high patient satisfaction and compliance. Proponents of the Boston bracing system advocate for a team model wherein the surgeon, orthotist, and physical therapist apply their specific expertise and knowledge in combination to fabricate a brace and treatment plan that provides for the greatest chance of successful treatment.³²

The Rigo Chêneau Style Brace (Fig. 104.5)

The Rigo Chêneau style brace was developed in Spain by Dr. Manuel Rigo in the early 1990s and, as the name suggests, represents an adaptation of the earlier Chêneau theory of bracing. The Rigo Chêneau brace has a highly contoured, multiplanar design that acts through three-point curve correction, derotation and counter-rotation of the curve, and sagittal correction. Brace shape is determined through application of a scoliosis classification system which includes both radiographic and clinical criteria. In addition, the brace provides open space over the curve concavity that allows rib cage expansion during breathing. This active force assists in the repositioning of trunk muscles and remodeling of the rib cage as it expands into the volumes allowed by the contours of the brace.

The role of physical therapy in treatment with the Rigo Chêneau brace deserves special mention as the brace's emphasis on active correction through guided breathing facilitates synergy between the corrective action of the brace and the corrective action of scoliosis specific exercises.²²

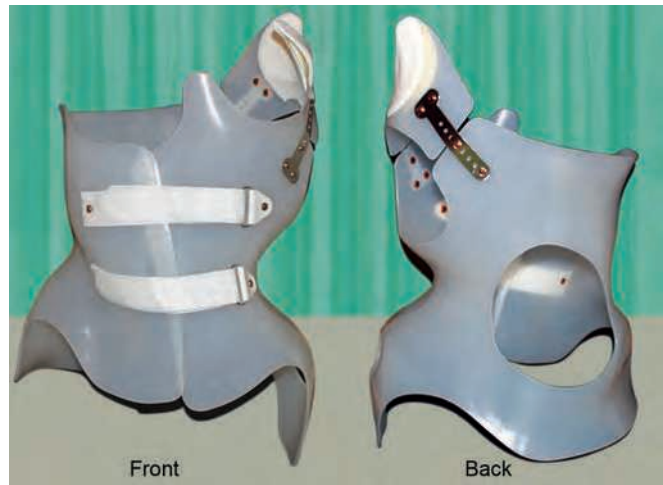


Fig. 104.5: The Rigo Chêneau style brace.

Night-time Bracing

The benefits of night-time bracing include improved patient compliance as night-time wear circumvents the psychosocial and self-image issues that accompany brace-wearing. The thought is that for a select group of patients with significant compliance issues, some brace wearing is better than none. Additionally, night-time brace wear allows patients to remain physically active during the course, which some have hypothesized may promote spontaneous correction.^{34,35}

Charleston Bending Brace (Fig. 104.6)

Hooper's Charleston bending brace was developed in 1978 primarily to address compliance issues in patients with AIS in whom other treatment options had failed.

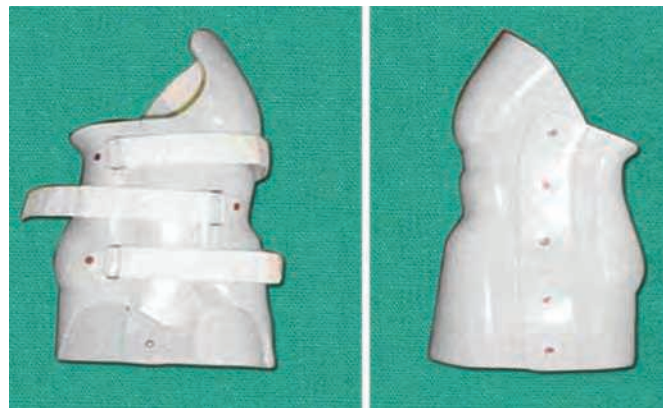


Fig. 104.6: Charleston bending brace.

The Charleston brace operates on the principles that dominated original bracing techniques such as Lovett and Brewster's turnbuckle brace, i.e. passive bending of the spine without traction can promote correction of spinal deformity by inducing stretching forces on the concavity of the curve and compression at the convexity. This technique is applied most effectively in patients with single lumbar or thoracolumbar curves between 25° and 40°,^{33,34} and in these cases effectiveness has been shown to be comparable to the Boston brace.³⁵ A study of the Charleston bending brace's biomechanics has confirmed that the major effect of the brace on the scoliotic curve consists of unloading the tensile and compressive forces as was hypothesized by the brace's designers. However, there is some concern that this method of bracing can negatively affect compensatory curves.³⁶

Providence Brace (Fig. 104.7)

Similar to the Charleston brace, the Providence brace is designed for night-time use only, as it severely limits mobility; however, the Providence brace applies lateral and rotational forces to bring the deformity toward the midline rather than simply bending the spine. Creation of the Providence brace involves placing the patient in the supine position and creating a plaster cast of the torso while applying the desired derotational and apical forces through use of lumbar and stabilizing pads. Similar to the Charleston brace, this plaster cast becomes a positive mold of the corrected torso from which a polypropylene brace incorporating the standard pressure and void regions is formed. The resulting orthosis has been shown to be effective in addressing rotation, as well as double curves and some thoracic curves under 35°, though correction of higher thoracic curves is typically less successful.³⁷ Special care should be taken to avoid excessive pressure that may result in patient discomfort, pressure sores, and noncompliance.



Fig. 104.7: Providence brace.

Soft Braces: The SpineCor Brace

The SpineCor brace represents a departure from the traditional rigid bracing options and operates on the theory that addressing the factors that confound effective bracing—namely, noncompliance due to the appearance of and discomfort created by rigid bracing—will lead to better outcomes. The SpineCor bracing method uses a flexible plastic pelvic base as the anchor for elastic bands that connect to a cloth vest and apply corrective force while promoting normal posture. Force and directionality of the elastic bands are determined through three-dimensional computerized reconstruction of the patient's posture using software provided by the manufacturers.³⁸

The application of the brace is similar to that of existing TLSOs, where the patient is instructed to use the brace a minimum of 20 hours per day. As this is a relatively new corrective device, a limited body of evidence exists to support its use, though a prospective study from 2008 showed that progression of the curve during treatment was significantly higher in subjects using the SpineCor brace compared to those using more traditional, rigid bracing systems (Table 104.3).³⁹

Table 104.3: Application and indication for brace types.

Brace	Application	Indication
Boston lumbar brace	Daytime TLSO	Apex below L1; 20°–45° curve
Boston thoracolumbar brace		Apex from L1–T10; 20°–45° curve
Boston thoracic brace		Apex from T10–T7; 20°–45° curve
Rigo Chêneau style brace	Daytime TLSO	Apex from T-6 to below L-1; 20°–45° curve
Charleston brace	Nocturnal bending brace	Single thoracolumbar and lumbar curves from 25°–40°; Risser sign of 0–2
Providence brace	Nocturnal brace	Thoracolumbar and lumbar curves <35°

Bracing Practice

Indications

The goal of bracing in the AIS population is to halt the progression of scoliosis. Therefore, the indications for bracing are in large part guided by the risk of curve progression and skeletal maturity of the child. For example, in Sponseller's review of bracing for AIS,⁴⁰ it is suggested that curves of 25°–45° in children with Risser Signs of 0–1—indicating the potential for rapid growth—should be offered a brace on initial evaluation. A number of clinical and radiographic indicators exist to gauge the potential for curve progression and the skeletal maturity of the child.

The specific role of genetics in the natural history of AIS is an area of growing interest for researchers. A large body of evidence supporting a hereditary component of scoliosis makes a positive family history of progressive scoliosis particularly concerning for progression in the child.^{41–43} Gender and maturity are also implicated in accelerated progression.¹⁰ Females are reported to have a higher incidence of AIS as well as a higher risk of progression than males.^{44,45} Additionally, markers of physiologic immaturity also raise concern for progression. These include younger age, premenarchal status, and lower Tanner staging. Radiographic imaging can also suggest progression, as Risser signs of 0–1 suggest that significant skeletal growth remains. More recently, Sanders's Simplified Tanner-Whitehouse-III staging classification has been used in this population, with a score of 4 or lower indicating an increased risk for curve progression.^{6,46}

The relative contraindications to bracing are related to the nature of the curve and the medical and emotional health of the patient. Children with high thoracic curves may be difficult to brace as the shoulder girdle is poorly tolerated and lordotic thoracic spines have also proved difficult to brace.⁴⁰ The risk of progression decreases as patients near skeletally maturity, and initiation of bracing in late-adolescence is unlikely to change the course of the child's scoliosis. Overweight children have been reported to experience higher rates of failure with bracing, which is likely due to the interference of excess body mass on the brace's transmitted corrective forces.⁴⁷ Medical conditions that may limit or prevent the use of a brace include respiratory and digestive problems. Furthermore, behavioral and mental health issues such as attention deficit hyperactivity disorder, anxiety, autism, and psychosis can lead to noncompliance or even physical harm to the child.

Bracing Protocol, Follow-up, and Cessation

Once the decision to brace has been made, the time in-brace and follow-up intervals must be determined by the provider. Following collaboration by the orthotist and provider to create the brace, Sponseller suggests an in-brace radiograph with a minimum 30% correction of thoracic curves and 50% correction of thoracolumbar and lumbar curves to be adequate.⁴⁰ If in-brace correction fails to reach 15–20%, the appropriateness of the brace for the child should be reevaluated. Our department's practice is to time the first in-brace radiograph at 4–6 weeks following the initiation of bracing. This allows for patients to become accustomed to the brace and brings issues pertaining to comfort and feasibility to the attention of the provider.

The recommendation for time spent daily in-brace ranges from 12 to 23 hours, depending on the source. Katz et al. reported that progression of scoliosis while treated with a Boston brace was inversely related to the number of hours spent in-brace, and patients who utilized the brace for >12 hours per day experienced the best outcomes. BrAIST reported a treatment success rate of >90% among patients who wore their braces 12.9–17.6 hours per day.¹⁶ However, patient compliance must be considered on an individual basis when making brace-time recommendations.⁴⁸ For example, if a patient is highly compliant, a prescription to use the brace for 20 hours/day, may be a reasonable recommendation. On the other hand, if a relatively noncompliant patient could only handle 14 hours/day in-brace, prescribing more time may be a discouraging obstacle. Overall, data does suggest that control of progression of AIS is more likely when a patient is in-brace for a minimum of 12 hours/day.⁴⁸ If a patient is unable to meet in-brace time requirements, then the appropriateness of bracing should be reevaluated.

After the initial in-brace radiograph and recommendations for use are provided, a follow-up interval of 4–6 months is appropriate. Brace comfort and any reports of skin breakdown should be investigated as these can lead to noncompliance and dermatologic issues. Based upon the fit of the brace and growth of the patient, it may be appropriate to create a new brace at the discretion of the orthotist or provider. Patients should be directed to abstain from bracing for 24 hours prior to follow-up appointments where out-of-brace radiographs will be obtained as curve progression can be masked by radiographs taken in the brace. In addition, bone age X-rays for Sanders score,

pelvic films to evaluate the triradiate cartilages, and Risser sign should also be taken to assess the patient's skeletal maturity.

Cessation of bracing should be considered if the child is skeletally mature or if there is failure to control progression of the curve. Signs of skeletal maturity include a growth history of <1 cm within a 6-month interval, female patients beyond 1-year postmenarche, and radiographic findings such as a Risser sign of 4–5, Sanders 7–8, or closed distal radial physis.⁴⁰ If follow-up radiographs reveal significant curve progression despite bracing, then cessation of bracing should be considered.

PHYSICAL THERAPY

Physical therapy is a somewhat controversial nonoperative treatment option for AIS. Scoliosis-specific exercises (SSE) are taught to patients by therapists who are especially trained in these methods and they aim to reduce the deformity caused by scoliosis. While this modality is commonly used in Europe, it remains controversial in the United States and is used variably in clinical practice.

History

Exercise-based treatment for scoliosis dates back to Hippocrates and has been used for centuries in Europe.⁴⁹ The modern era of treatment for scoliosis with physical therapy began in Germany in the 1920s with the development of a program by Katharina Schroth. The initial Schroth therapy program focused on inpatient postural correction, proprioception, and breathing techniques, and was followed by daily home exercises. While the foundation

of Schroth therapy is essentially unchanged today, certain aspects of the treatment have evolved over time, including an adaptation of the therapy for outpatient settings.⁴⁹ The most recent development in Schroth-based therapy is the concept of integrated scoliosis rehabilitation (ISR), which incorporates therapy into activities of daily living. Other scoliosis-specific programs with similar principles to the Schroth method have been developed in recent years, including Dobomed, Side-shift, and SEAS (Scientific Exercises Approach for Scoliosis).⁵⁰

Indications

There are no evidence-based indications for the use of physical therapy in AIS patients; however, experts in scoliosis-specific physical therapy published consensus indications in 2006 that vary based on the patient's Cobb angle and level of skeletal maturity. Patients who are ideal for treatment with outpatient physical therapy alone are those patients who have small curves (15°–25°) and significant remaining growth (i.e. Risser 0; Sanders <4). Physical therapy is recommended in combination with brace treatment when skeletally immature patients reach a Cobb angle of 25° and have a high risk for curve progression.⁵¹ One relative indication to consider in any patient who may be a candidate for scoliosis-specific physical therapy is whether or not they are motivated to participate in a time-intensive therapy program and perform daily exercises on their own. Therefore, patients and family members who chose to undergo this therapy must be adequately counseled about the requirements of this treatment (Fig. 104.8).



Fig. 104.8: Schroth patient.

Source: Available from <http://www.schrothmethod.com>.

Methods of Treatment

Autocorrection is one of the primary principles of SSE, and is defined as the ability of a patient to improve their deformity through active postural realignment of the spine in three dimensions.⁵⁰ Schroth-based programs are designed specifically for each patient based on their individual curve pattern, and they focus on improving scoliotic posture, postural proprioception, and breathing patterns through “elongation, realignment of trunk segments, arm positioning, and corrective muscle tension.”⁶⁰ Dobomed, Side-shift, and SEAS therapies are based on similar principles but use slightly different approaches to achieve curve correction. It is important to note that SSE are different from general physical therapy, which often includes low-impact stretching and strengthening exercises, which the literature has shown to be ineffective for treating scoliosis.⁵⁰

The initial Schroth program was designed to include 4–6 weeks of inpatient therapy, followed by home exercises for 30 minutes per day after the initial treatment period. Many treatment studies have used this model, although the program has also been adapted for outpatient use. The period of outpatient therapy may be modified to fit the needs of each patient, with as little as 3–4 months of therapy for 2 hours per day and twice per week, although these individual modifications to the program have been less clearly studied. Following the initial intensive period of therapy, patients are instructed to perform daily home exercises.⁴⁹

Evidence for the Use of Physical Therapy

Several studies argue that scoliosis-specific physical therapy programs, both inpatient and outpatient, have the ability to decrease curve magnitude and progression.^{52–56} The goals of physical therapy are to decrease bracing requirements, prevent the need for surgery, improve physical appearance (i.e. rib hump), improve pulmonary function, and/or to decrease the psychological burden of the curve deformity.⁵⁷ A 2011 systematic review identified 20 studies that investigate the utility of physical therapy in AIS treatment, and the authors concluded that exercises can be effective in reducing the curve progression rate and/or improving Cobb angles, as well as reducing brace prescription. It should be noted that the evidence quality of the studies in this review is low—only one randomized-controlled trial is included, and the majority are

retrospective and many lack controls.⁵⁰ A Cochrane review published in 2012 cites two studies (154 patients) with low-quality evidence for the benefit of physical therapy in AIS, and it found that “better quality research needs to be conducted before the use of SSE (SSE) can be recommended in clinical practice.”⁵⁸ These papers highlight the need for more rigorous research to be performed in order to determine whether physical therapy programs are truly beneficial to AIS patients.

In addition to curve correction, an improvement in vital capacity has been demonstrated in two studies; however, it is unclear whether this effect is clinically significant.^{59,60} Curve correction through physical therapy may also decrease the rate of chronic back pain that has been demonstrated in adult patients with a history of AIS.⁸ The potential psychological and general health benefits of an exercise-based treatment program should not be overlooked; patients who participate in this type of therapy may benefit from improvements in overall body image and self-confidence through the completion of daily exercises. This type of treatment requires the patient to actively participate in their own treatment program, and therefore improvements in appearance and function further empower and motivate patients to participate in their own care (see Fig. 104.7).

Difficulties with Physical Therapy Treatment

A major criticism of physical therapy as a treatment for AIS is that there is weak evidence to support its use and long-term benefits, leaving many physicians skeptical of its true utility. Nearly all of the data demonstrating the success of this therapy comes from a few centers in Europe, and it is unclear if these results are replicable in other patient populations throughout the world. It is also unclear if the beneficial effects of this therapy are maintained once therapy is discontinued. Furthermore, because physical therapists must be trained in SSE programs, access to adequately trained therapists will be an issue for many patients. Frequent long distance travel may not be feasible for many patients, and there may be additional financial burdens for family members as a result of their child's therapy sessions.

While the use of physical therapy as a treatment for AIS remains controversial in the United States, there is potential for research growth in this area. A positive prospective trial would improve the support for its use, but as it stands,

this therapy remains an unproven, resource-intense treatment modality with limited evidence for effectiveness. Regardless, it still may serve as a low-risk treatment option for highly-motivated patients who wish to avoid bracing and surgery.

OTHER TREATMENT MODALITIES

There exist other treatment modalities in AIS beside observation, bracing, and physical therapy. However, these treatments are neither well studied nor supported by evidence. Chiropractic or osteopathic manipulation, acupuncture, exercise, and nutritional therapies have all been asserted as possible treatments or adjuncts to treat AIS, and all have little to no support for their use.⁶¹ Finally, electrical stimulation of spinal musculature has been explored to treat progressive AIS, but this has shown to be less effective than bracing.⁶²⁻⁶⁴

CONCLUSION

Nonoperative management of AIS is generally reserved for those patients who are at risk of progression due to skeletal immaturity. The most commonly employed treatment methods are observation, bracing, and physical therapy. If the risk of progression is deemed high by the provider as evidenced on history, physical examination and radiographic findings, then halting the progression of the curve becomes a therapeutic priority. The BrAIST trial has provided strong evidence that bracing of curves between 25° and 45° is more effective than observation at preventing progression to surgery when compliance is ideal. Physical therapy has been shown to be at least temporarily efficacious in select patients as well, but the demands of these methods are often prohibitive for children and their families. Therefore, it is important for providers to understand the select populations of patients that may benefit from these nonoperative therapies. Furthermore, it is important to take the appropriate measures to understand the patient from a holistic perspective in order to determine the optimal treatment course for the child and their family.

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This study is a systematic literature review that included 18 studies pertaining to bracing versus observation with the endpoint of surgery for the indication of AIS. They found that bracing and observation showed no clear advantage with similar rates of surgery in each group, although no recommendation could be made due to the low levels of evidence the studies exhibited.

Nachemson A, Peterson L. Effectiveness of treatment with a brace in girls who have adolescent idiopathic scoliosis. A prospective, controlled study based on data from the Brace Study of the Scoliosis Research Society. *J Bone Joint Surg.* 1995;77:815-22.

This prospective, center-randomized, international study with 286 girls showed that bracing with a Boston TLSO was successful in 74% of patients compared to 34% in the observation cohort. Follow up was 4 years following initiation of brace and this is high-level evidence toward the efficacy of bracing.

Sponseller PD. Bracing for adolescent idiopathic scoliosis in practice today. *J Pediatr Orthop.* 2011;31(1 Suppl):S53-60. This review article is a synthesis of the evidence pertaining to bracing as well as a protocol description of bracing practice.

Fusco C, Zaina F, Atanasio S, et al. Physical exercises in the treatment of adolescent idiopathic scoliosis: an updated systematic review. *Physiother Theory Pract.* 2011;27(1):80-114.

A systematic literature review about the effectiveness of physical exercise/therapy in AIS. It summarizes the literature and differing techniques of physical exercise/therapy. They found that physical exercise/therapy can improve outcome measures in AIS.

Operative Treatment of Adolescent Idiopathic Scoliosis

Daniel Sucato, John Vorhies

Snapshot

- » Surgical Indications
- » Preoperative Planning
- » Operative Technique
- » Outcome
- » Complications

SURGICAL INDICATIONS

The goals of operative intervention in AIS are to prevent progression of the curve, correct the three-dimensional deformity, and obtain a balanced spine. Curve magnitudes $>50^\circ$ at the time of skeletal maturity have a propensity to progress throughout adulthood despite cessation of growth.¹ Progression of deformity in untreated AIS has been associated with back pain, cosmetic concerns, restrictive pulmonary disease in large curves, and a negative self-perception of health.²⁻⁷ Therefore, a spine curvature $>45^\circ$ in immature patients and 50° in mature patients is indicated for spinal fusion.







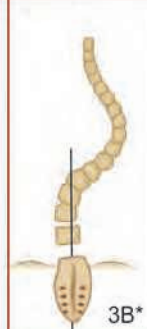
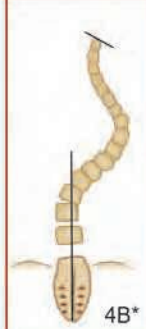




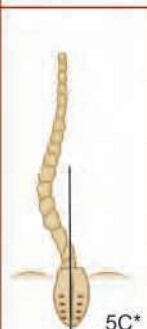



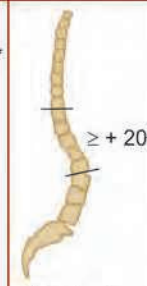
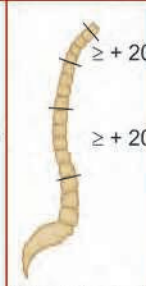
PREOPERATIVE PLANNING

Surgical intervention in AIS presently involves placement of instrumentation to anchor rods to the spine, correction of the deformity via mechanical methods, and fusion of the instrumented segments to maintain the corrected spinal alignment. The methods for achieving correction and fusion include anterior and posterior spinal approaches. The major decision-making during preoperative planning involves selection of the approach, identifying the major and minor curves that require instrumentation, and select the appropriate spine segments to instrument to correct and balance the spine—all while preserving the maximum number of motion segments in the spine.

Classification

The King classification first described patterns of deformity to allow prediction of fusion levels in AIS with major thoracic curves. Based on their review of 405 patients with AIS, they created a uniplanar classification system guiding distal fusion levels to adequately balance the coronal plane deformity.⁸ The primary focus was to ensure that the distal fusion level was centered over the sacrum, and specifically for King type II curves, a selective thoracic fusion could be performed to achieve that result.⁸ Limitations of this classification system included absence of the sagittal and axial planes and fair to poor intra- and interobserver reliability, necessitating a more comprehensive classification system.⁹⁻¹²

In 2001, Lenke et al. published a new classification system that described the deformity in both the coronal and the sagittal plane (Fig. 105.1).¹³ They identified three components that helped guide the extent of spinal fusion in AIS—curve type (1–6), lumbar (L) spine modifier (A, B, C), and a sagittal thoracic modifier (–, N, +), and proved that it was reproducible among a group of seven independent spine surgeons from the Scoliosis Research Society (SRS) (Fig. 105.1).¹⁴ The L spine modifier refers to the relationship between the apex of the L curve and the center sacral vertical line (CSVL): A—CSVL is between the pedicles, B—CSVL touches the apical vertebral body, C—CSVL

Lumbar spine modifier	Curve type (1–6)					
	Type 1 (main thoracic)	Type 2 (double thoracic)	Type 3 (double major)	Type 4 (triple major)	Type 5 (TL/L)	Type 6 (TL/L-MT)
A (No to minimal curve)	 1A*	 2A*	 3A*	 4A*		
B (Moderate curve)	 1B*	 2B*	 3B*	 4B*		
C (Large curve)	 1C*	 2C*	 3C*	 4C*	 5C*	 6C*
Possible sagittal structural criteria (to determine specific curve type)	 Normal	 PT kyphosis	 TL kyphosis	 PT + TL kyphosis		

*T5–T12 sagittal alignment modifier: -, N, or +
 - is $<10^\circ$ N (normal) is $10\text{--}40^\circ$ + is $>40^\circ$

Fig. 105.1: The Lenke classification—type 1, thoracic; type 2, double thoracic; type 3, double major (thoracic $>$ lumbar); type 4, triple major; type 5, thoracolumbar/lumbar; type 6, double major (lumbar $>$ thoracic). Lumbar modifier A—center sacral vertical line (CSVL) is between pedicles on apical lumbar vertebra, B—CSVL touches apical lumbar vertebra, C—CSVL is medial to apical lumbar vertebra. Thoracic modifier (-)— $<10^\circ$ T5–T12 kyphosis, (N)— $10^\circ\text{--}40^\circ$ T5–T12 kyphosis, (+)— $>40^\circ$ T5–T12 kyphosis.

Table 105.1: Suk classification of three-dimensional deformities of thoracic.

	<i>Thoracic</i>			
	<i>Single</i>		<i>Double</i>	
	<i>A</i>	<i>B</i>	<i>A</i>	<i>B</i>
	Distal NV = EV+1(0)	Distal NV = EV + 3	Distal NV = EV + 1(0)	Distal NV = EV + 3
Distal fusion	NV or EV + 1(0)	NV - 1 or EV + 2	NV or EV + 1 (0)	NV - 1 or EV + 2
Distal DVR	Opposite direction	Same direction	Opposition direction	Same direction

(DVR: Direct vertebral rotation; NV: Neutral vertebra; EV: End Vertebra).

Table 105.2: Suk classification of three-dimensional deformities of lumbar.

	<i>Lumbar</i>			
	<i>Double major</i>		<i>Thoracolumbar/Lumbar</i>	
	<i>A</i>	<i>B</i>	<i>A</i>	<i>B</i>
	Bend film: L3 crosses CSVL L3 rotation on bend film < GII	Bend film: L3 doesn't cross CSVL L3 rotation on bend film < GII	Bend film: L3 crosses CSVL L3 rotation on bend film < GII	Bend film: L3 doesn't cross CSVL L3 rotation on bend film < GII
Distal fusion	L3	L4	L3	L4
Distal DVR	Opposite direction	Opposite direction	Opposite direction	Opposite direction

(DVR: Direct vertebral rotation; CSVL: Center sacral vertical line).

is medial to the apical vertebral body. The sagittal thoracic modifier refers to the amount of kyphosis measured between T5 and T12: (-) <10°, (N) 10°–40°, (+) >40°. Numerous studies have affirmed the validity of the Lenke classification in determining fusion levels, identifying curve patterns amenable to selective fusion, and preventing postoperative decompensation.^{15–18}

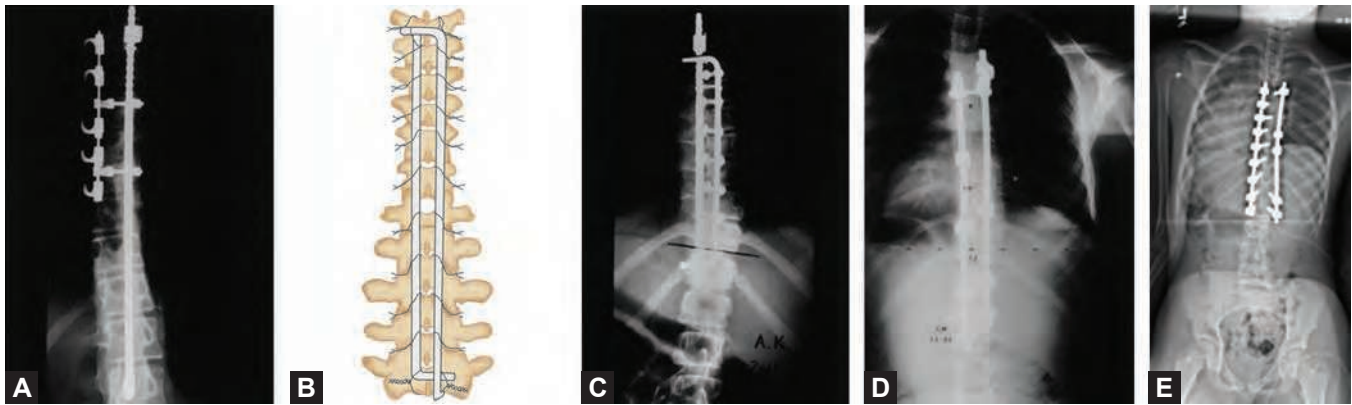
Suk et al. has created a classification system that aims to better characterize the three-dimensional deformity, guide fusion levels, and direct treatment of the deformity in all planes.¹⁹ Consisting of four curve types: thoracic—single and double, and L—single and double, the distal fusion level is determined based on two types of curves, A and B. For thoracic curves, the A and B characterization depends on the relationship between the end vertebra (EV) and neutral vertebra (NV): A—distal NV is within one of the EV; B—the distal NV is located two to three levels caudal to the EV. For L curves, the A and B characterization depends on the position of L3 on bending films—its relation to the CSVL and the Nash-Moe rotation. Distal direct vertebral rotation (DVR), as a means to derotate the uninstrumented portion of the spine and improve correction while limiting the extent of fusion, is a standard concept in addition to apical DVR. Other concepts intrinsic to

Suk's classification include pedicle screw instrumentation, a rigid rod for derotation and complete pedicle fill on the concave side of the spine. The selection of thoracic/lumbar and A/B guides the direction of the distal DVR and the lowest-instrumented vertebra (LIV) (Tables 105.1 and 105.2).¹⁹

The Lenke classification is most commonly utilized for describing curve patterns and drives preoperative decision-making regarding the extent of spinal arthrodesis. However, it does not capture the three-dimensional character of the scoliotic deformity. The SRS is currently developing a new three-dimensional classification system.^{20,21}

Flexibility

Assessing the flexibility of the spine preoperatively is helpful primarily for assessing the structural nature of the minor curves and determining the proximal and distal extent of the fusion, and secondarily, for providing insight into the amount of correction attainable during surgery. King,⁸ Lenke,¹³ and Suk¹⁹ all use supine side-bending films to determine the structural nature of curves and guide the extent of fusion. Traction films demonstrate more curve flexibility when assessing curves >50° compared to side-bending and



Figs. 105.2A to E: Evolution of spinal instrumentation. (A) Harrington instrumentation, (B) Luque instrumentation, (C) Wisconsin segmental spinal instrumentation, (D) Cotrel-Dubousset instrumentation, (E) pedicle screw instrumentation.

push-prone radiographs.²²⁻²⁵ However, selecting distal fusion levels based on traction films results in a higher incidence of “adding on” and should be avoided.²⁵ Push-prone films are helpful to assess the response of the uninstrumented spine to correction of the primary curve, especially in selective thoracic fusion.^{26,27} Radiographs assessing the flexibility of the spine should be used to assist in determining the extent of fusion, but ultimately levels should be chosen according to the standing posteroanterior and lateral radiographs.

Magnetic Resonance Imaging

The value of a preoperative magnetic resonance imaging (MRI) lies in identifying any underlying spinal pathology that is causing the scoliosis and should be addressed prior to deformity correction surgery. Indications for MRI include an abnormal neurologic examination including asymmetric abdominal reflexes,²⁸ left thoracic curve, and absence of thoracic apical lordosis.²⁹⁻³³ Patients with presumed AIS and a normal physical and neurologic examination do not require a preoperative MRI.³⁴

Intraoperative Neuromonitoring

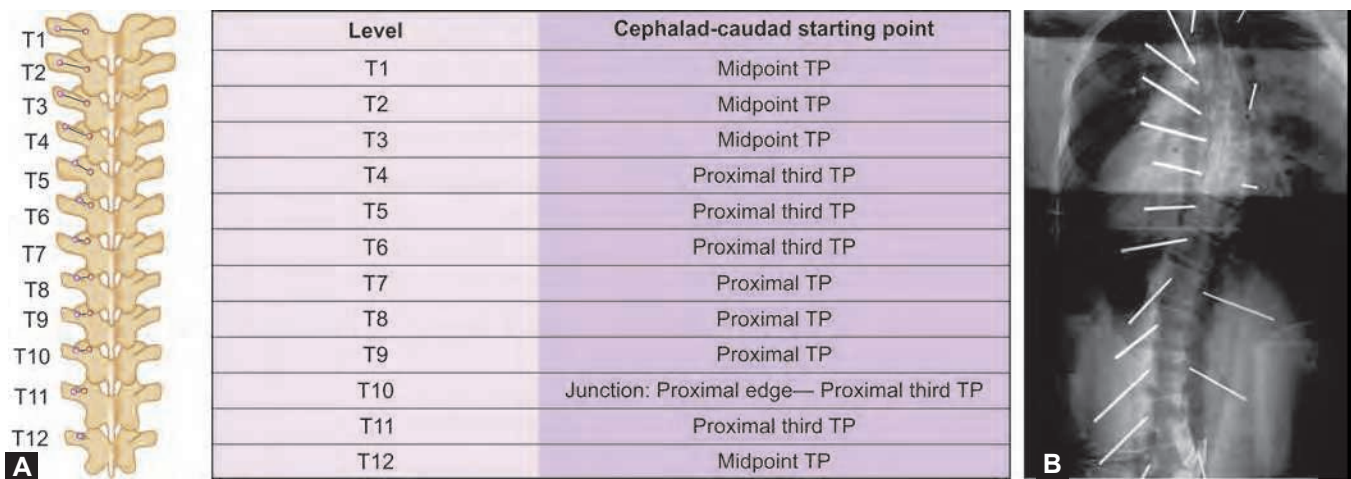
The most devastating complication from scoliosis surgery is neurologic injury; therefore, it is paramount to utilize intraoperative neuromonitoring. The Stagnara wake-up test was first employed to assess gross motor function during surgery.³⁵ Possessing significant limitations including premature extubation, patient recall, prolonged surgical time, and the potential for false positives and negatives, the Stagnara wake-up test was replaced by intraoperative spinal cord monitoring beginning in

the late 1970s.³⁶⁻³⁸ Somatosensory-evoked potentials were the first neuromonitoring technique instituted and continue to be a part of current monitoring strategies while TcMEPs have become the standard of care for monitoring motor pathways.³⁹⁻⁴² Somatosensory-evoked potentials and TcMEPs are adequately sensitive and specific to warrant a prompt response by the surgeon when a critical change in monitoring occurs to avoid the potential for a neurologic deficit.^{39,41}

OPERATIVE TECHNIQUE

Surgical treatment of AIS includes an anterior, posterior, or combined approach with instrumentation and fusion. Traditionally, an anterior approach is beneficial for preventing the “crankshaft phenomenon”⁴³ when substantial growth remains in an immature patient, i.e. open triradiate cartilages. The anterior approach also offers an advantage over the posterior approach, as fusion levels can typically be limited to EV to EV. The posterior approach allows for exposure of the spine to the width of the transverse processes, meticulous facetectomies and preparation of the bony surface to allow for fusion, and placing instrumentation with hooks and/or pedicle screws to achieve arthrodesis.

The evolution of spine instrumentation is closely associated with the deformity correction techniques that corresponded with that implant system. Distraction-based Harrington rod instrumentation (Fig. 105.2A)⁴⁴ was followed by Luque double L-rod segmental instrumentation that used wires to draw the spine to the rods (Fig. 105.2B). The Wisconsin segmental spinal instrumentation system was a



Figs. 105.3A and B: Pedicle screw placement. (A) Freehand technique—anatomical location of thoracic pedicles to properly identify and place pedicle screws in the thoracic spine. (B) Suk et al. technique of placing a Kirschner-wire in each pedicle to be instrumented and obtaining a single radiograph to ensure proper placement.⁵⁷

hybrid of Harrington and Luque techniques and avoided intracanal instrumentation (Fig. 105.2C).^{45,46} Cotrel and Dubousset introduced the concept of derotating the spine with a concave rod-rotation maneuver (Fig. 105.2D).⁴⁷ This technique was employed initially utilizing hooks as the anchor points to the spine, and subsequently has been replaced by pedicle screws in a hybrid (Fig. 105.2E) or all-pedicle screw construct. Much debate exists involving the superiority of hybrid versus all-pedicle screw constructs with the weight of the literature favoring all-pedicle screw constructs for improved pulmonary function,^{48,49} greater coronal correction,^{49,50} better maintenance of coronal and sagittal correction,⁵⁰ less LIV tilt,⁴⁹ fewer revisions,⁵¹ greater improvement in main thoracic (MT) scolimeter measurements,⁴⁹ fewer spine segments instrumented,⁵² and higher patient satisfaction.^{49,50,53} Hybrid instrumentation outperforms pedicle screw constructs in restoring kyphosis,^{52,54} avoiding proximal junctional kyphosis,⁵⁵ surgery time,⁵⁰ and blood loss.⁵⁰

Safe placement of pedicle screws is paramount to successfully performing PSF. Numerous techniques have been described to place thoracic pedicle screws safely including freehand (Fig. 105.3A),⁵⁶ plain radiograph or fluoroscopic-guided (Fig. 105.3B),⁵⁷ and computed tomography-navigated techniques.^{58,59}

Selective Thoracic Fusion

A mindset for preserving spinal motion should influence the identification of curves to include in the fusion

mass. Performing a selective thoracic fusion indicates instrumenting the major thoracic curve in the presence of a minor thoracolumbar (TL)/L curve that crosses the midline and will be left untreated. The benefit of preserving the lumbar motion segments must be balanced by the ability to achieve spinal balance with a selective thoracic fusion and to correctly identify lumbar curves that will not progress. The Lenke lumbar modifier (B or C)¹³ helps identify these curves, in addition to objective radiographic parameters of the major and minor curves relative to each other—Cobb angle [MT/compensatory lumbar (CL) >1.2, apical vertebral rotation measured by Nash-Moe⁶⁰ (MT/CL >1.0), and apical vertebral translation ratios (MT/CL >1.2).^{61–63} The clinical appearance, e.g. rib and lumbar prominences and trunk balance, provides insight into the structural nature of a curve and whether the patient will tolerate the residual deformity. Lastly, the distal extent of a selective thoracic fusion must correlate with the sagittal profile to avoid junctional kyphosis.

Selective thoracic fusion, when levels are properly selected, has good surgical outcomes.⁶⁴ The uninstrumented L curve will correct an average of 19–66%^{61,65,66} and SRS-24 results will be good provided coronal balance has been restored.⁶¹ Pedicle screw instrumentation results in greater thoracic and spontaneous L correction compared to hybrid constructs.^{66,67} Risk factors for “adding-on” or coronal decompensation include an LIV that is two levels proximal to the NV⁶⁶ or an LIV that is proximal to the stable vertebra⁶⁵ (Fig. 105.4).

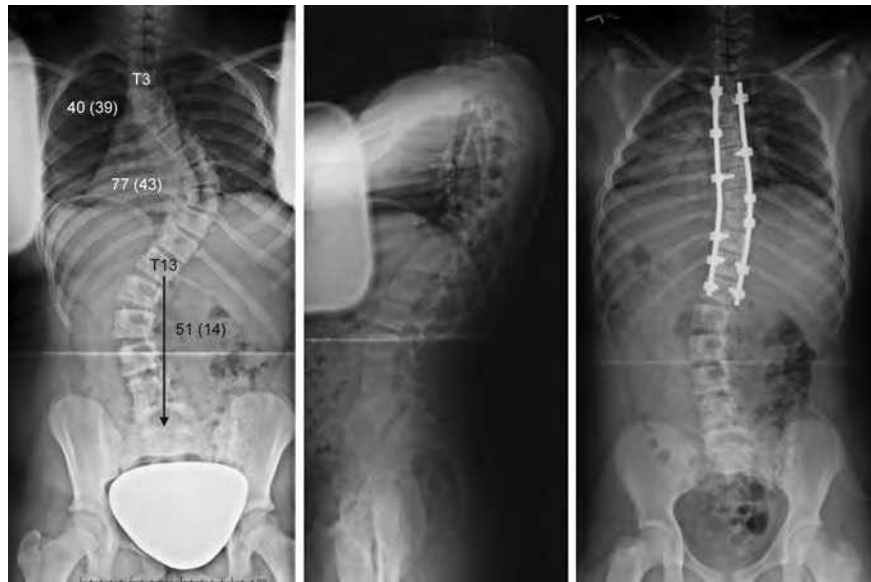


Fig. 105.4: Selective thoracic fusion. Properly balanced selective thoracic fusion with the stable vertebra being selected as the lowest instrumented vertebra.

TL/L Curves

Major structural curves of the TL or L spine are possible candidates for selective fusion as well. A nonstructural thoracic curve $<50^\circ$ with a bend to $\leq 20^\circ$, TL/L: thoracic Cobb ratio ≥ 1.25 , and closed triradiate cartilages can be considered for selective TL/L fusion from an anterior approach.⁶⁸ Traditionally, this approach involves the spine segments from EV to EV and is able to gain excellent correction while saving fusion levels compared to a posterior approach.⁶⁹ Shufflebarger et al. demonstrated that a posterior approach with an all pedicle screw construct from EV to EV was effective at correcting the deformity.⁷⁰ A comparative study between two practices demonstrated significantly better curve correction, less loss of correction at minimum 2-year follow-up, and shorter hospital stays for posterior, all-pedicle screw constructs compared to anterior instrumented fusions.⁷¹ Therefore, TL/L curves can be instrumented from an anterior or posterior approach with positive results (Fig. 105.5).

Double and Triple Major Curves

Combined thoracic and L structural curves require PSF with instrumentation. Proximal and distal fusion levels must include all structural curves to prevent decompensation.^{72,73} The LIV should be touched by the CSVL, the caudal disc should not open to the convexity, and the LIV should not have significant rotation.

Direct Vertebral Rotation

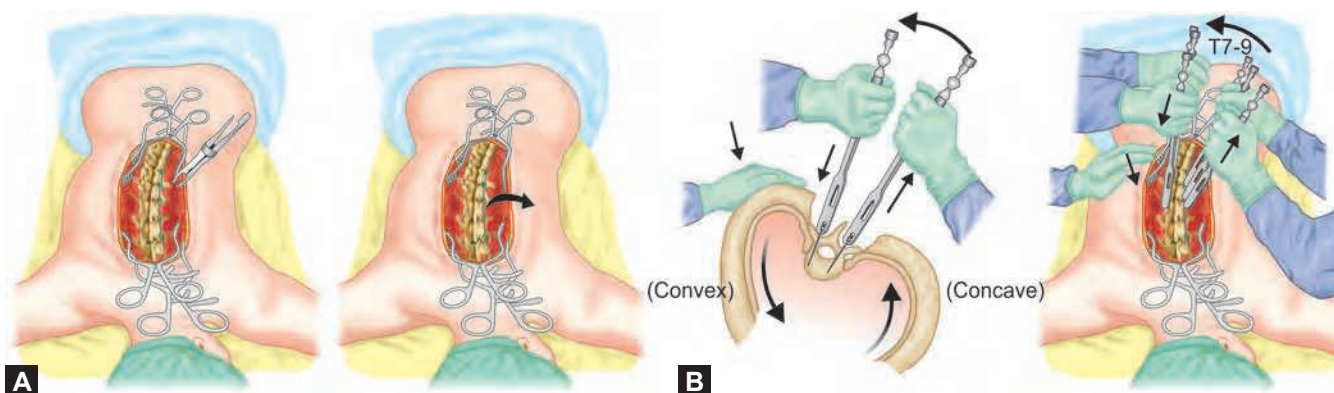
Direct vertebral rotation is a mechanism for correcting the axial plane spine and chest wall deformity associated with scoliosis. As first described by Lee et al. in 2004, thoracic scoliosis is first corrected by a precontoured rod placed into the concave, segmental pedicle screws and a derotation maneuver is performed.⁷⁴ Then, DVR is performed by rotating the screws in the juxta-apical vertebrae, on the concave and convex sides, opposite to the direction of the rod derotation; and then all the concave screws are sequentially tightened to the rod (Figs. 105.6A and B).⁷⁴ This maneuver results in greater coronal curve correction,^{74,75} less hypokyphosis,⁷⁶ decreased LIV tilt,^{74,75} less LIV rotation,⁷⁴ higher SRS-22 self-image scores,⁷⁷ and a ~50% reduction in the rib deformity.^{76,77}

70°–100° Curves

Advance degrees of spinal curvature in AIS have often led to an anterior release to gain flexibility followed by a posterior spinal instrumented fusion. With the advent of all-pedicle screw constructs, equivalent deformity correction is achieved with posterior-only approaches and does not have a detrimental effect on pulmonary function.⁷⁸⁻⁸⁰ Alternatively, a prone thoracoscopic release can be performed with a PSF without any adverse effect on pulmonary function.⁸¹



Fig. 105.5: Thoracolumbar fusion from a posterior approach. Appropriate correction and restoration of sagittal balance with an all-pedicle screw construct from a posterior approach instrumenting the major curve from end vertebra to end vertebra.



Figs. 105.6A and B: Direct vertebral rotation (DVR): A technique for correcting the axial plane deformity. (A) As described by Lee et al., correction of the scoliosis is performed first by performing a rod rotation maneuver to derotate the spine and correct the coronal and sagittal plane deformity. (B) Then, DVR is performed at the apical vertebra on both the concave and convex pedicle screws followed by securing the concave rod to the pedicle screws.

Other techniques for larger, stiff curves include various osteotomies—Ponte, pedicle subtraction, and vertebral column resection (VCR). The Ponte osteotomy involves resection of the inferior articular processes of the cephalad vertebra and the superior articular processes of the caudal vertebra.⁸² A variation on the Ponte osteotomy, the wide posterior release, has been advocated in the L spine to improve coronal and sagittal plane correction,^{70,71,83} and some surgeons employ these techniques in the thoracic spine to gain flexibility as well. Specific techniques for

correcting kyphosis and restoring sagittal balance include the pedicle subtraction osteotomy that gains 31.7° of sagittal plane correction, and the Smith-Petersen (Ponte-type) osteotomy, which gains 10.7° of correction per spine segment.⁸⁴ Vertebral column resection is an aggressive maneuver rarely indicated in AIS, with possible consideration in curves >100°. A posterior-only approach allows three-column resection of singular or multiple vertebral segments at the apex of the deformity allowing powerful correction, albeit with significant risk.⁸⁵

OUTCOME

Adolescent idiopathic scoliosis patients who undergo PSF typically have good results—the SRS 24 has demonstrated statistically significant improvement 2 years after surgery in pain, general self-image, function from back condition, and level of activity.⁸⁶ At 5 years after surgery there was a statistically significant increase in back pain compared to the 2-year postoperative scores, and a trend toward worsening in the other four domains despite patient satisfaction scores not changing.⁸⁷ However, overall results remained improved relative to their preoperative scores. Pulmonary function is improved when a posterior-only approach is used to achieve arthrodesis.⁸⁸⁻⁹¹ The patient's ability to return to activity is related to flexibility and is statistically correlated with a lower Lenke classification, a higher SRS-22 score, and the distal extent of fusion—a stepwise decline in return to activity exists, as instrumentation is carried distally from LIV T11 to L4.⁹²

COMPLICATIONS

Preoperatively, thoughtful planning can mitigate potential intraoperative and postoperative complications. Adequate selection of levels, choosing the appropriate implants and approach, and understanding the patient's anatomy all correlate to successful deformity correction and spinal balance. Intraoperative complications are mostly related to incorrect implant placement, but can also include excessive blood loss, spinal cord perfusion problems, inadequate fusion preparation or limited bone graft, and using bulky instrumentation, e.g. crosslinks, that can lead to pseudarthrosis. Neurophysiologic monitoring with SSEPs and TcMEPs is necessary for deformity correction. The surgeon must respond to every critical change—raise patient's body temperature, ensure mean arterial blood pressure is >80–90 mm Hg, and reversing any spinal instrumentation placed or correction performed prior to the critical change.

Postoperative complications include neurovascular compromise, failure of hardware, medical issues, and wound infection. The overall complication rate in a recent SRS report was 6.3% with a mortality rate of 0.02% for all idiopathic scoliosis cases.⁹³ This is similar to an earlier SRS report in AIS patients of 5.2% and 0.03%, respectively.⁹⁴ A new neurologic event occurred in 0.75% of idiopathic cases,⁹³ which is in line with prior reports in the AIS population by Diab et al., 0.69%,⁹⁵ and Coe et al., 0.5%.⁹⁴ The infection rate from the SRS report was 1.4%.⁹³

KEY POINTS

- Correction of deformity and spinal arthrodesis is indicated in skeletally immature adolescent idiopathic scoliosis (AIS) patients with curves >45°, and >50° in skeletally mature AIS patients.
- Preoperative classification and assessment of structural and nonstructural curves aids in selecting appropriate proximal and distal levels for fusion. The Lenke classification provides the most reproducible guidance for surgical planning.
- Selective thoracic fusions are advantageous when they result in appropriate correction and spinal balance while preserving spinal motion.
- Posterior spinal fusion (PSF) with pedicle screw instrumentation affords a similar ability to correct deformity and balance the spine as anterior approaches without an adverse effect on pulmonary function.
- Safe performance of spinal instrumentation and deformity correction involves neurophysiologic monitoring with somatosensory-evoked potentials (SSEPs) and transcranial motor-evoked potentials (TcMEPs).

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KEY REFERENCES

Weinstein SL, Ponseti IV. Curve progression in idiopathic scoliosis. *J Bone Joint Surg Am*. 1983;65:447-55.

This study provides a natural history of untreated AIS and provides evidence for progression of curves despite cessation of spinal growth. They establish that thoracic and lumbar curves $>50^\circ$ progress after maturity at an average rate of 1° /year. This provides evidence supporting the recommendation for operative intervention in curves $>50^\circ$.

Newton PO, Faro FD, Gollogly S, et al. Results of preoperative pulmonary function testing of adolescents with idiopathic scoliosis. A study of six hundred and thirty-one patients. *J Bone Joint Surg Am*. 2005;87:1937-46.

The authors demonstrate a correlation between AIS and diminished pulmonary function. They provide evidence for the impact of the scoliotic deformity on the chest and enhance the indication to intervene surgically to prevent worsening and seek improvement in pulmonary function.

Lenke LG, Betz RR, Harms J, et al. Adolescent idiopathic scoliosis: a new classification to determine extent of spinal arthrodesis. *J Bone Joint Surg Am*. 2001;83-A:1169-81.

The Lenke classification is the current standard for describing AIS curves and guiding proper selection of levels to include in the fusion. The authors describe the deformity in both the coronal and sagittal plane and demonstrate good intra- and interobserver reliability.

Lee SM, Suk SI, Chung ER. Direct vertebral rotation: a new technique of three-dimensional deformity correction with segmental pedicle screw fixation in adolescent idiopathic scoliosis. *Spine (Phila Pa 1976)*. 2004;29:343-9.

The technique described by the authors directly affects the axial plane deformity. Following correction of the coronal and sagittal plane deformity with a rod rotation maneuver, the apical vertebra are directly rotated to cause an improvement in rib prominence, greater coronal plane correction, and improve SRS-22 image results.

Reames DL, Smith JS, Fu KM, et al. Complications in the surgical treatment of 19,360 cases of pediatric scoliosis: a review of the Scoliosis Research Society Morbidity and Mortality database. *Spine (Phila Pa 1976)*. 2011;36:1484-91.

A report by the SRS Morbidity and Mortality committee demonstrating an overall complication rate of 6.3% and a new neurologic injury rate of $<1\%$. It establishes AIS deformity correction surgery as a safe procedure.

Anterior Lumbar and Thoracolumbar Correction and Fusion for AIS

Gene Cheh, Yongjung J Kim

Snapshot

- » Indications
- » Selection of Fusion Level
- » Surgical Approach
- » Postoperative Care
- » Discussion

INTRODUCTION

Open anterior instrumented fusion for scoliosis surgery started from the use of a flexible cable by Dwyer in 1964.¹ After Dwyer cable, anterior instrumented fusion has evolved from Zielke instrumentation (a single screw/3.5-mm single threaded rod—still kyphosing and a significant incidence of pseudarthrosis) to single screw/4.5-mm single rod systems and double screw/double rod system combined with structural grafting (structural allograft vs. titanium cages).²⁻⁴ Structural graft with cages or structural allograft can produce lordotic sagittal alignment, load sharing, and allows application of compression during instrumentation. The advantages of anterior instrumented fusion of thoracolumbar/lumbar (TL/L) (type 5) curves include saving fusion levels both proximally and distally by fusing only the Cobb measurement of the curve from the upper end vertebra to the lower end vertebra.⁵ Significant rotational correction can be achieved by direct vertebral derotation and by aggressive removal of anterior soft tissues including the annulus, disc, and posterior longitudinal ligament (PLL). Solid anterior fusion also may remove the risk of crankshaft in skeletally immature patients.⁵

Anterior approach has become less commonly indicated because strong multidirectional correction using pedicle screws has changed surgical decision-making in adolescent idiopathic scoliosis. However, thoracolumbar retroperitoneal approach is still a viable option in the treatment of thoracolumbar-lumbar curves (Lenke type

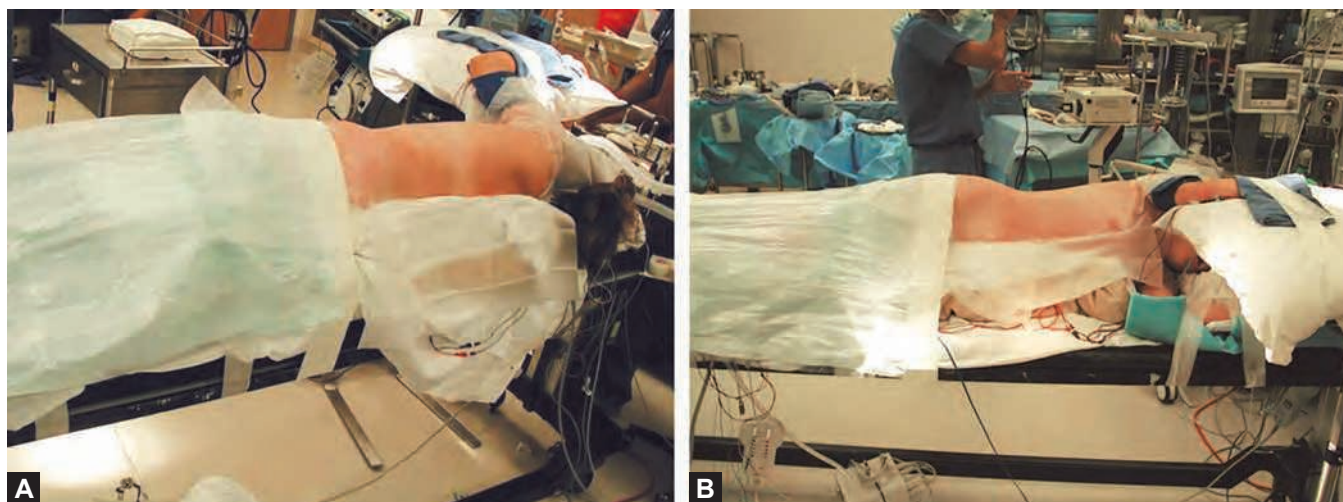
5 curve). It facilitates excellent clinical and radiographic outcomes with relatively short fusion. This approach can be useful in some double major curve (Lenke type 6) with large lumbar curves and notable L4 and L5 coronal plane obliquity. After anterior instrumented fusion, improved alignment of distal unfused segments was observed. The indications for, techniques of, results and complications of, single and dual rod instrumentation for idiopathic scoliosis correction as well as comparative analysis to posterior approach will be detailed in this chapter.

INDICATIONS

Anterior thoracolumbar or lumbar instrumentation and fusion may be indicated in Lenke type 5-TL/L adolescent idiopathic scoliosis (AIS) curve when the magnitude of curve is $>40^\circ$.⁶ In addition, the TL/L portion of a double major adolescent idiopathic scoliosis with large lumbar curves in Lenke Type 3 and 6 curves may be approached with a preliminary anterior instrumented fusion prior to an instrumented posterior spinal fusion (PSF) of both curves. These indications are rare, but often performed to maximize the correction of the TL/L portion of large lumbar curves and notable L4 and L5 coronal plane obliquity with significant rotation and cosmetic malalignment.⁷

SELECTION OF FUSION LEVEL

The level of selected fusions includes all vertebrae between upper end vertebra and lower end vertebra. Sometimes



Figs. 106.1A and B: (A) Lateral decubitus position from the back. (B) Lateral decubitus position from the front.

extremely short anterior instrumentation/fusion principle by Hall/ Millis technique is helpful for very flexible thoracolumbar curves. If a vertebral body is the apex, then one disc and body above/one disc and body below are selected to be fused. If a disc is the apex, then two vertebral bodies, one disc above/two vertebral bodies, one disc below are to be fused.⁸ Sometimes choosing the lowest instrumented vertebra (LIV) at L3 versus L4 is challenging when the disc below L3 is parallel or only slightly wedged into fractional lumbosacral curve. Poor selection of L3 as LIV with a significant disc wedging at L3–L4 disc or out of gravity line (away from center sacral vertical line) may induce earlier degeneration in the future. Flexibility of lumbosacral fractional curve, the disc angle below LIV, and rotation of LIV should be carefully considered to prevent LIV with a significant disc wedging at L3–L4 disc or out of gravity line (away from center sacral vertical line) significantly.⁹

SURGICAL APPROACH

Positioning

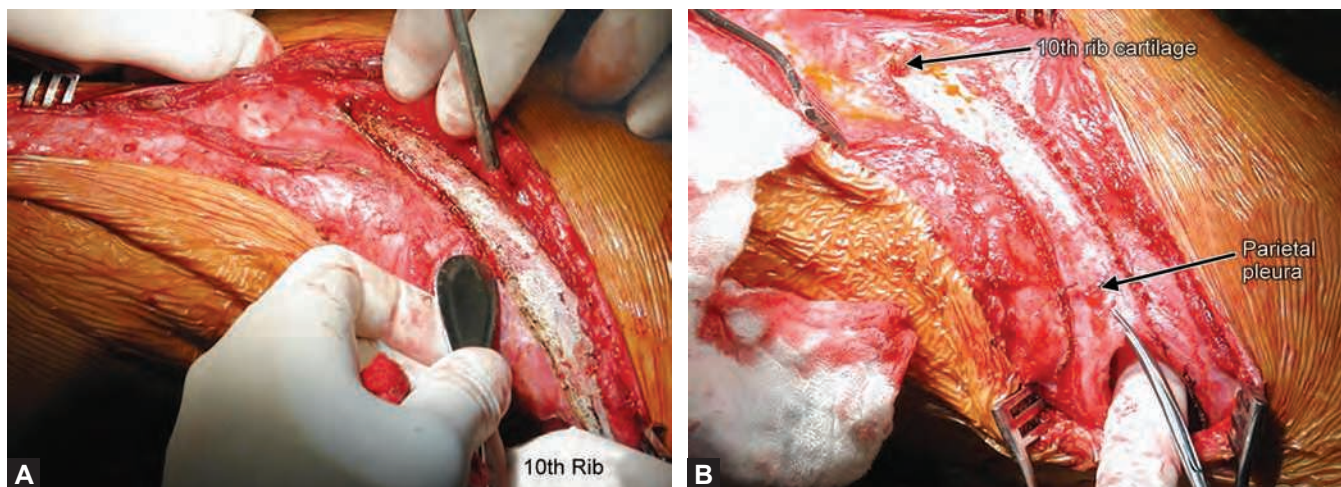
In anterior scoliosis surgery, the spine should be approached on the side of the convexity of the TL/L curve. The patient is positioned in a lateral decubitus position and held securely in bean bag. Pressure points are padded and pillows are placed between the legs (Figs. 106.1A and B).

Exposure

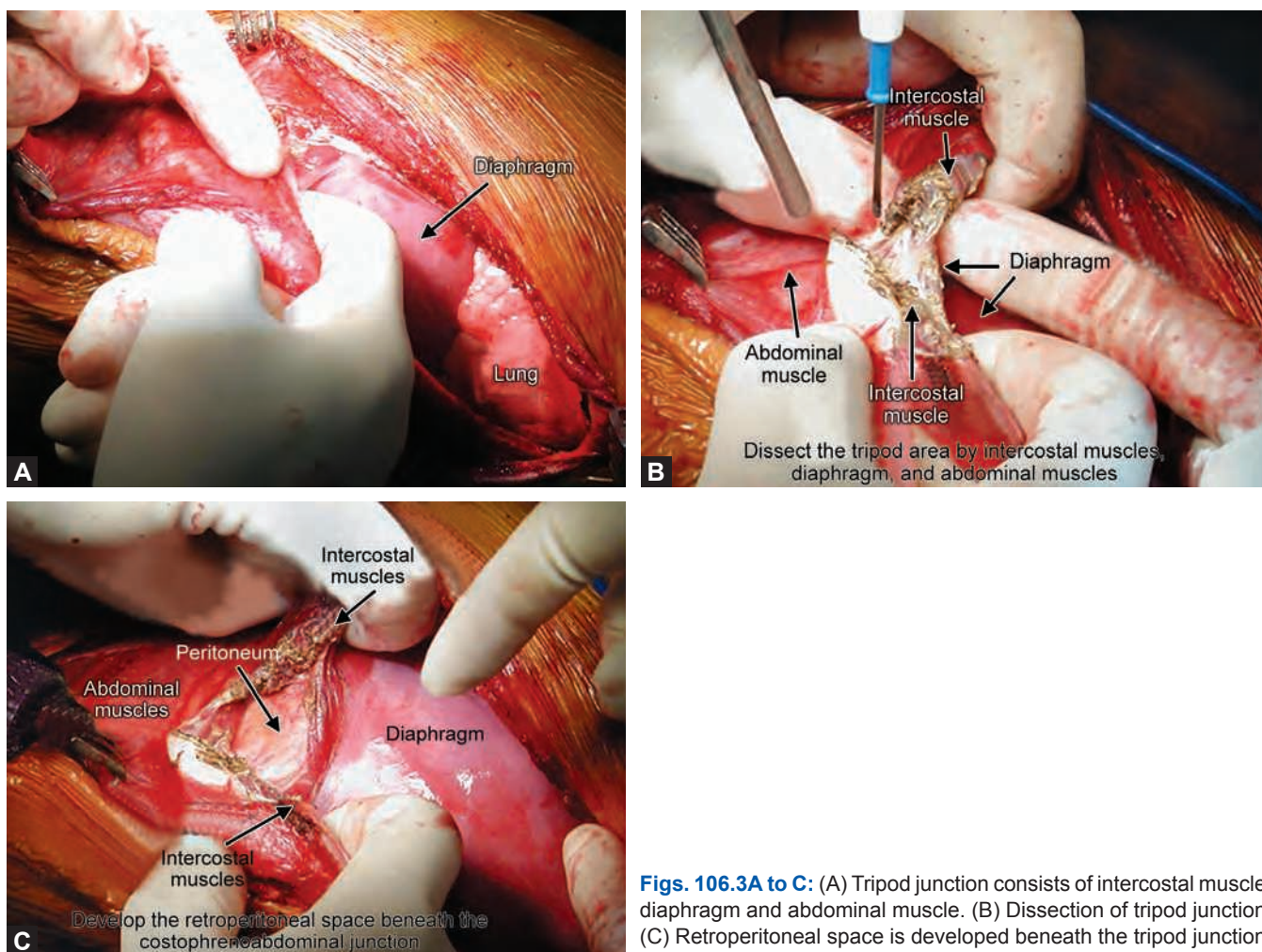
The skin incision begins in the mid-axillary line, follows the course of the tenth (or ninth) rib as far as the costal

cartilage, and then continues obliquely downward on the upper and middle abdomen, toward the lateral border of the rectus abdominus. The 10th rib may be identified by counting up from the 12th rib and is the lowest rib that is attached to chondral cartilage. After division of the latissimus dorsi and serratus anterior proximally, external oblique muscle of the abdomen that runs parallel to the skin incision from the costochondral junction area is divided to reveal the underlying internal oblique muscle. The 10th rib is exposed. The periosteum of the 10th rib is transected with the electrocautery. After complete exposure of the 10th rib, excise the rib from the costal cartilage to angle of the rib leaving no sharp edge (Fig. 106.2A). Then pack the rib bed with a gel foam or bone wax. Pick up the periosteum and parietal pleura and make a small incision with knife. Open the thoracic cavity with the Metzenbaum scissors and pack the lung (Fig. 106.2B). The costal cartilage is divided with a knife or dissected below the cartilage after a tagging suture. After dividing the external oblique muscle, internal oblique muscle, and transverse muscle of the abdomen in the direction of skin incision below the costal cartilage, carefully expose the preperitoneal fat. This is the very important entrance to the retroperitoneum and later marker for wound closure (Figs. 106.3A to C).

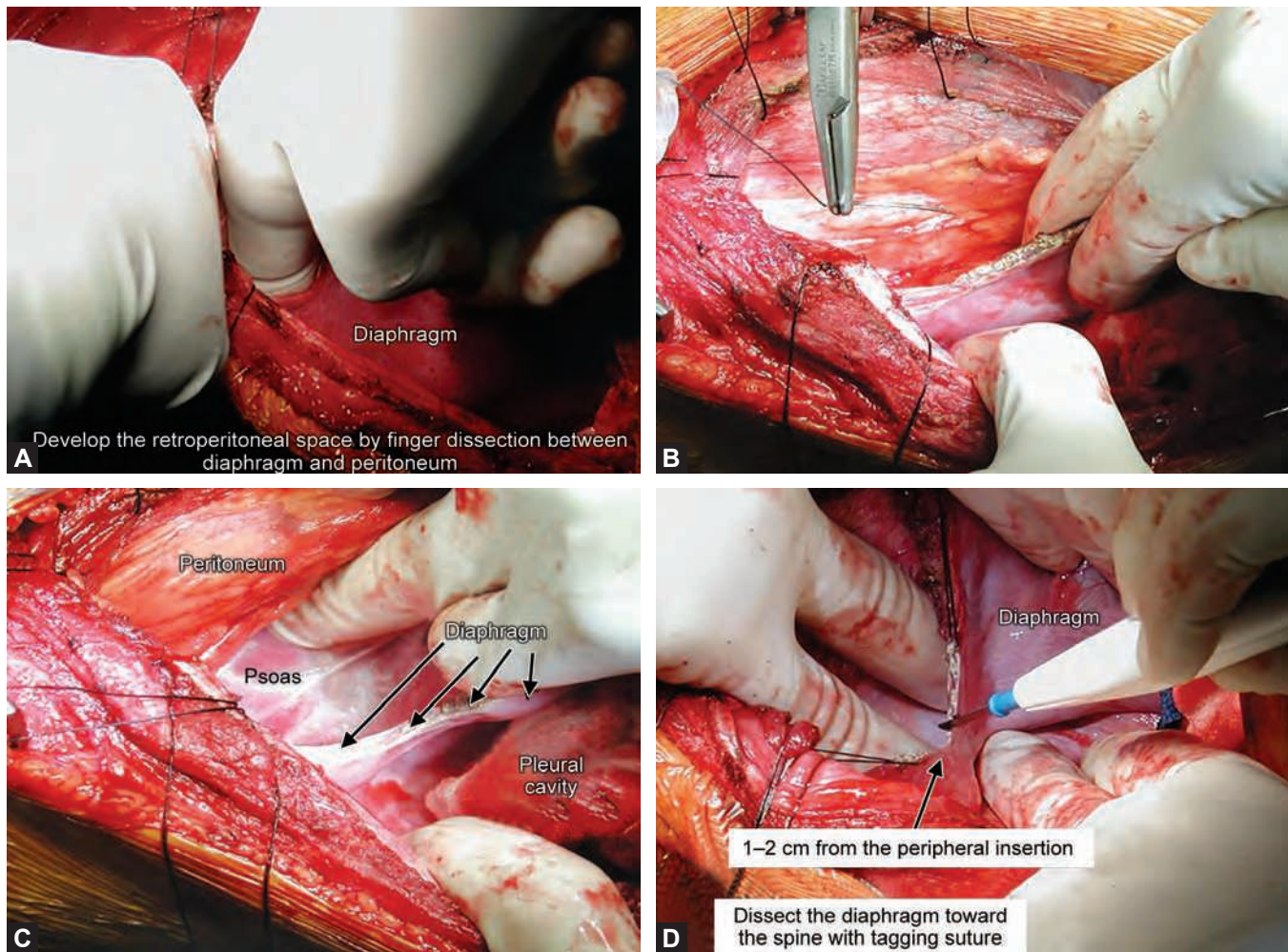
After identifying the preperitoneal fat below the abdominal muscles, retract the peritoneum medially from the lateral abdominal wall and downward from the underside of the diaphragm by using blunt dissection with gloved fingers and with a gauze on a forceps. This blunt dissection is needed toward the anterior surface of the quadratus lumborum and psoas muscles. Mobilize the peritoneum



Figs. 106.2A and B: (A) Periosteal elevator is used to detach the rib from underlying periosteum. (B) Thoracic cavity is entered by incising the parietal pleura using metzenbaum.



Figs. 106.3A to C: (A) Tripod junction consists of intercostal muscle, diaphragm and abdominal muscle. (B) Dissection of tripod junction. (C) Retroperitoneal space is developed beneath the tripod junction.



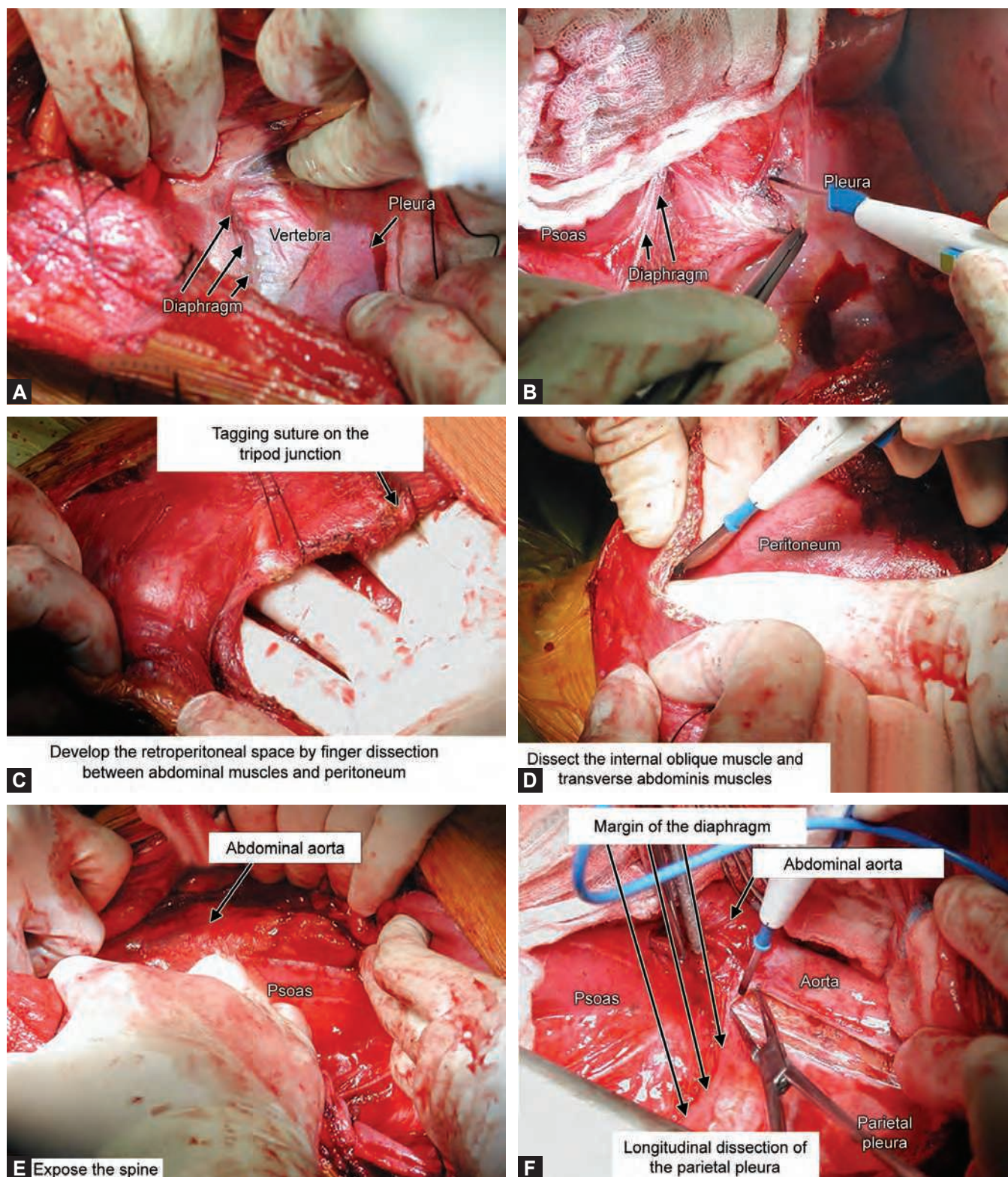
Figs. 106.4A to D: (A) Retroperitoneal space is developed by finger dissection between the diaphragm and peritoneum. (B) Tag sutures in the diaphragm for later closure. (C) Diaphragm is isolated. (D) Diaphragm is incised toward the vertebra.

off the lateral abdominal wall and from the undersurface of the diaphragm. Under the direct vision, the diaphragm is separated to vertebral column using the electrocautery preserving a 1-cm cuff of tissue by a curved incision that follows the lateral contour of the diaphragm. Damage to the phrenic vessels and nerves can be avoided by this peripheral dissection. The diaphragm is tagged along the way with markers for later closure (Figs. 106.4A to D).

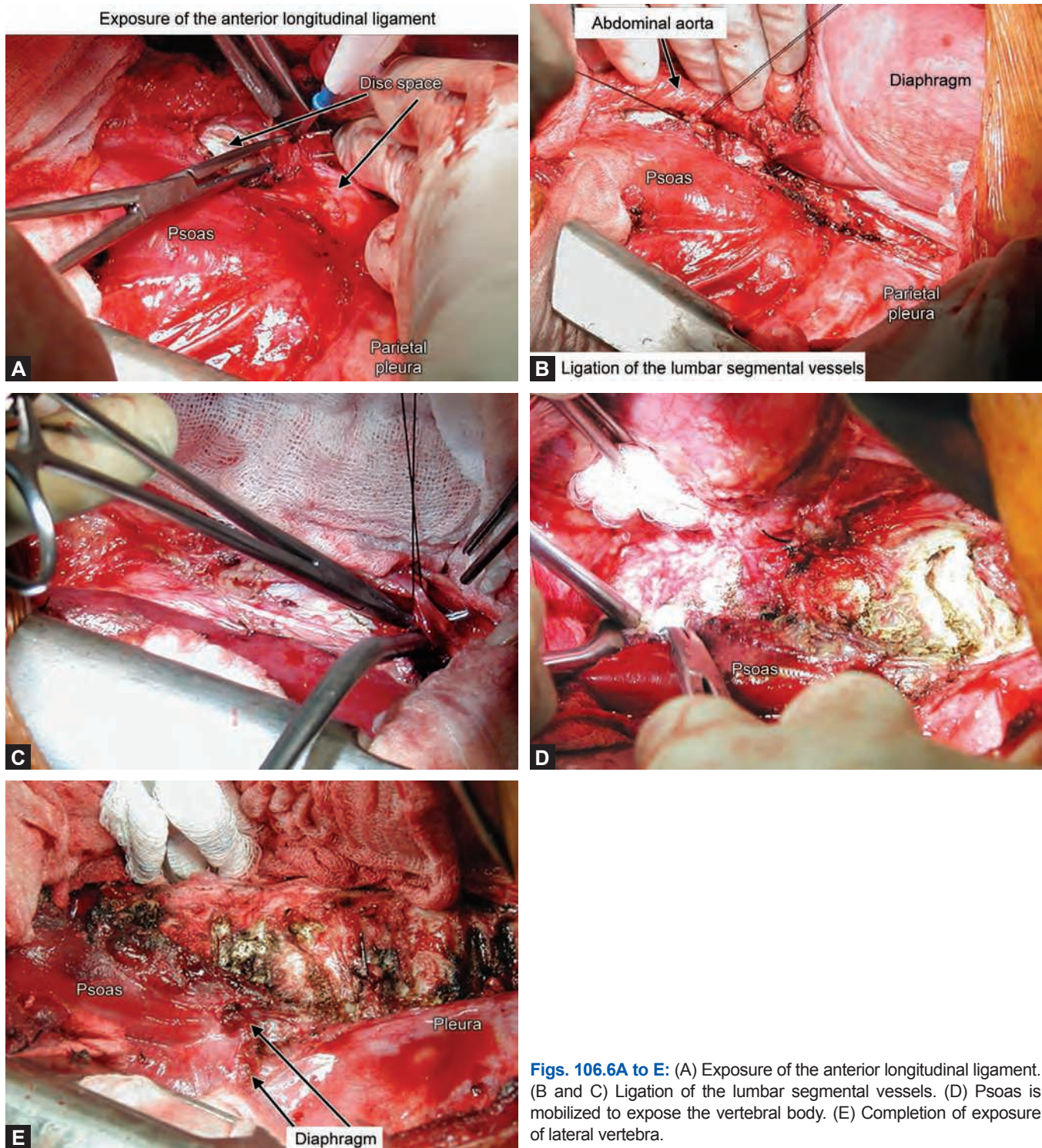
The diaphragm is incised down to the T12/L1 disc over the lateral and medial arcuate ligaments toward the crus in a radial fashion. The parietal pleura on the vertebrae to be accessed is incised with scissors along the vertebral column. The origin of the psoas major muscle is detached from the intervertebral discs and retracted posteriorly to expose the pedicle. Next the remaining abdominal muscles are divided in the direction of the

skin incision. The retroperitoneal space must be developed by the gloved finger dissection. Tagging sutures are used to mark corresponding portions of the muscle layer to help later closure (Figs. 106.5A to F).

The upper lumbar spine is exposed retroperitoneally. The peritoneal contents are swept anteriorly away from the quadratus lumborum and psoas muscle. Now self-retaining retractors can be placed to maintain the thoracotomy open and keep the peritoneal contents anteriorly. To expose the spine completely, split the parietal pleura longitudinally and ligate the segmental vessels to mobilize the great vessels. The segmental vessels on the vertebral bodies are ligated close to the aorta after detaching the psoas and cut. In the lumbar spine area, the psoas muscle should be mobilized to expose the lateral aspect of the vertebral body as far posteriorly as the base of the pedicle. Be cautious to stay in a strictly



Figs. 106.5A to F: (A) Diaphragm is incised to the T12-L1 disc. (B) Parietal pleura is incised. (C) Retroperitoneal space is developed between abdominal muscles and peritoneum. (D) Internal oblique and transverse abdominis muscles are cut. (E) Spine is exposed. (F) Parietal pleural is incised longitudinally to expose the vertebra.

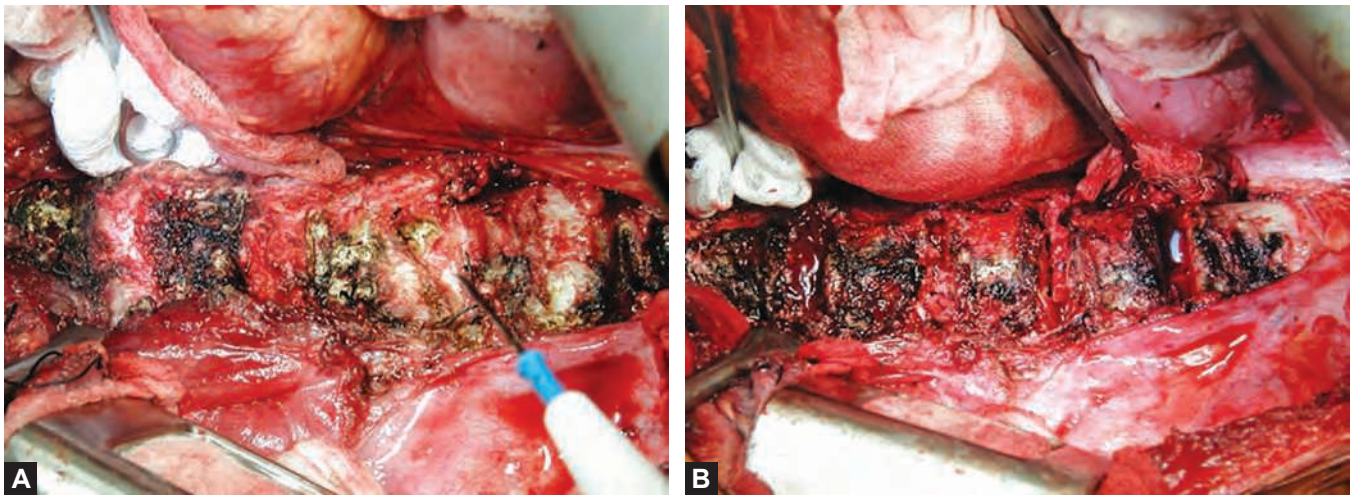


Figs. 106.6A to E: (A) Exposure of the anterior longitudinal ligament. (B and C) Ligation of the lumbar segmental vessels. (D) Psoas is mobilized to expose the vertebral body. (E) Completion of exposure of lateral vertebra.

subperiosteal plane to avoid bleeding from the segmental vessels within the psoas muscle. This type of bleeding is extremely difficult to control. At last, the spine is well exposed and the procedure can continue (Figs. 106.6A to E).

Discectomy

After exposure of the anterior and lateral aspects of the vertebral bodies to be instrumented, a thorough anulectomy and a discectomy are performed back to the PLL but not



Figs. 106.7A and B: (A) Annulectomy. (B) Discectomy and endplate preparation.

through the PLL. Care is taken to preserve the structural integrity of the vertebral endplates. A portion of annulus on the concavity was preserved to act as a hinge, to prevent overcorrection and to help hold bone graft in place (Figs. 106.7A and B).

Staples and Screws

Staples are applied to the lateral aspect of vertebral body, beginning proximally and distally and working centrally. The vertebral bodies are marked with electrocautery to identify the entry point of screws. An awl is used to create a pilot hole for the screws at mid-body, without angulation, at the top and bottom of the fusion levels. Be sure to position the staple posterior enough to allow placement of the anterior screw. Moving toward the apex of the deformity from either end, the screw entrance is developed progressively more posteriorly and is angled anteriorly to accommodate the axial rotation of the scoliosis. Each body then has a staple placed followed by a bicortical screw. Posterior screw is placed with 10° of anterior angulation, perpendicular to the base of staples. The posterior screw should be left slightly elevated off the staple's surface until the anterior screw is fully seated. Anterior screws are placed in a neutral position to place the screw perpendicular to the base of the staples. The alignment of the screws forms a relatively smooth arc, with the apex of the arc directed posteriorly. Screw placement is also determined, anticipating rod placement just posterior to the cages, to optimize lordotic contouring of the spine during compression. Bicortical purchase is especially critical at the ends of the construct where cantilever forces increase the risk of pullout.

Cages

After the screws are placed, but before the rods are secured, intradiscal bone grafting is performed at all fusion levels beginning at the most caudal disc space and working cephalad. A disc spreader is used in the posterior half of the disc space to keep the anterior half of the disc space open. The tallest structural titanium mesh cage that could be fit easily into the disc space is filled with morselized rib autograft and tapped into the anterior half of the disc space. Normally one or two cages are placed at each level. It is usually easier to insert two cages of smaller diameter (same height) rather than one larger diameter cage. The apical cages are placed in the deep concavity to allow for overcorrection of the apex in the coronal plane. In the sagittal plane, all cages are placed anteriorly in the disc to maximize lordosis. Posteriorly, morselized bone is placed against the decorticated endplates allowing for bleeding bone to contact the bone graft anteriorly, with the anterior endplates left intact to support the anterior structural grafts or cages. The disc spreader is removed, endplate decortication is performed around the cages, and morselized rib autograft is placed in the empty posterior disc space. Placement of cages at each successive cephalad disc space becomes tighter and more resistant to cage placement than the previous caudal level. This is acceptable, because when proceeding proximally, less segmental lordosis is required. Structural cages are placed at all fusion levels below T12. Fusion levels cephalad to T12 undergo endplate decortication followed by morselized rib autograft placement with the assistance of the disc spreader (Fig. 106.8).

Rods

Measurement of the appropriate rod length is accomplished by laying the flexible Bovie cord along the course of screws, marking the end with a hemostatic clamp. Make sure that it would not be too long, because the spine shortens on the instrumented side after compression. Posterior rod is contoured to accommodate anticipated coronal and sagittal alignments. During rod contouring, consideration of the desired sagittal alignment and coronal correction is made. The rod is marked at both ends to allow constant feedback for proper axial orientation during contouring, placement, and rod rotation. Rod is engaged proximally and cantilevered into the distal screws and captured at each level with set screws.

Deformity Correction

After the rod has captured all the screws, it is rotated 90° from posterior to anterior position to facilitate both

scoliosis correction and sagittal lordosis production by transforming the coronal curve into sagittal lordosis (Figs. 106.9A and B). Additionally, anterior translation of the apical instrumented levels derotates the spine. Alternatively, direct anterior vertebral body derotation can be performed. Screwdrivers are placed on the anterior screws at the apex of the construct. A direct vertebral body derotation maneuver is then performed whereby the screwdrivers and screws are then pushed down and rotated anteriorly to directly derotate the apical vertebral bodies while correcting the coronal plane malalignment simultaneously. With the vertebra being held in this derotated position, the posterior rod is engaged in the posterior set of screws, set bolts seated, and the rod is compressed from the apex to the ends (Figs. 106.10A and B). Visual inspection verifies coronal correction and sagittal alignment of the spine. Next, intervertebral compression is applied across the posterior screws beginning at the apex and working toward the ends of the construct. Gentle compression is used at the most proximal portion of the construct, because these screws are most susceptible to pullout. Intraoperative posteroanterior and lateral radiographs are then obtained to confirm appropriate placement of the instrumentation and the correction achieved. Then anterior rod is placed into screws and tightened without further attempt at correction. Lastly, the anterior rod is set in place with compression forces applied to that rod as well. Following anteroposterior and lateral intraoperative X-rays confirming optimal coronal and sagittal alignment, the set bolts are sheared off. Crosslink plates are placed to create rectangular construct for increased biomechanical rigidity. Occasionally, minor modifications of the compression

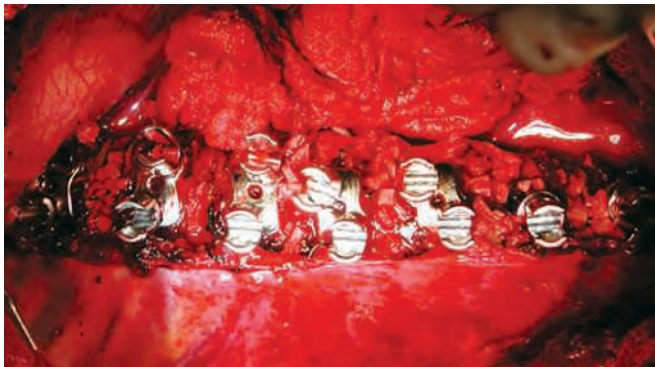
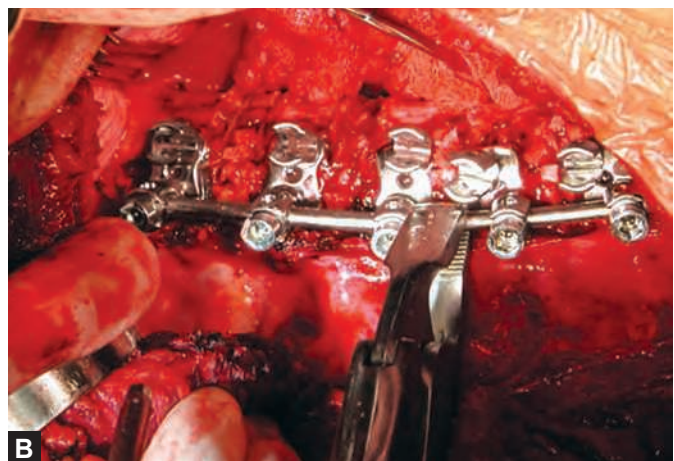
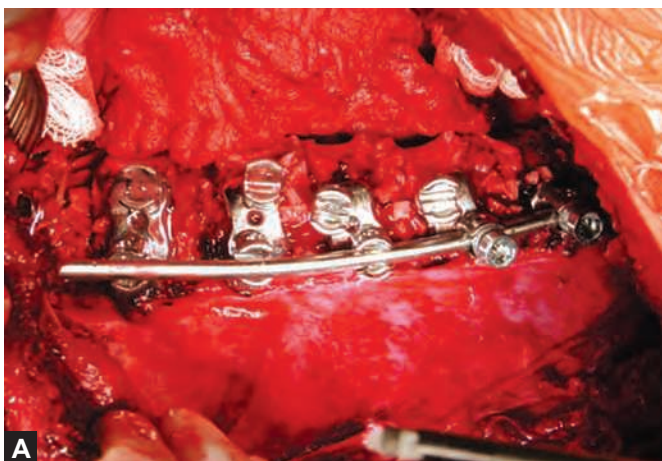
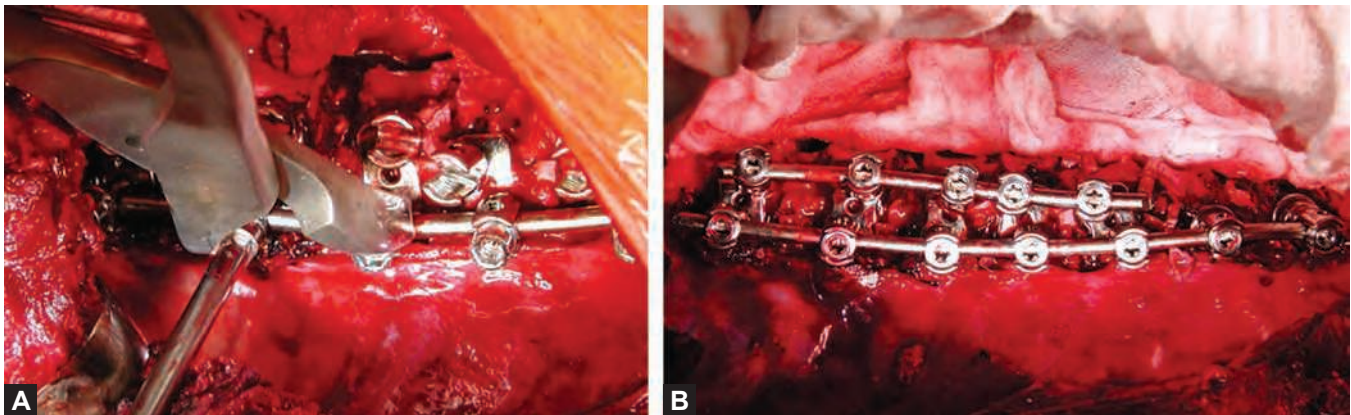


Fig. 106.8: Staples and screws are placed on the lateral vertebral body.



Figs. 106.9A and B: (A) Posterior rod placement. (B) Ninety degree rod rotation.



Figs. 106.10A and B: (A) Intervertebral compression across the posterior screws. (B) Placement of anterior rod.

or rod rotation are made to optimize correction. Care is taken to avoid overcorrection of the LIVs, which is verified by inspection of the disc alignment immediately below the LIV on the coronal intraoperative radiographs. Specifically, the goal is to have the inferior endplate of the LIV parallel to both the superior endplate of the next caudal segment and the top of the iliac crest. This is not always possible, given the residual secondary fractional lumbosacral curve. Additionally, there are cases in which the LIV is slightly overcorrected to improve coronal balance while preserving caudal motion segments. Pleural closure may then be performed, if desired, over the thoracic portion of this low profile system.

Closure

After the procedures on the vertebrae, close the parietal pleura to the original position with absorbable suture. The diaphragm is closed from the central dorsal direction toward the lateral ventral with multiple interrupted sutures of nonabsorbable suture, with care taken to reapproximate accurately using previously placed tag suture as a guide. The cartilage of the 10th rib is the landmark for the closure end of the diaphragm and meeting site to deep abdominal muscles. The internal oblique and transverse abdominus muscles are repaired as a single layer. After insertion of a chest tube with a separate stab incision, close the chest wall muscles—latissimus dorsi, serratus anterior, and external abdominal muscle layer by layer (Figs. 106.11A to E). Sometimes the rib resection gap is closed with the help of the rib approximator.

POSTOPERATIVE CARE

All patients are mobilized to stand by the bedside the day after surgery. Chest tube is kept to wall suction until drain-

age is <100 cc/shift on the 2nd and 3rd postoperative day. Ambulation is allowed as tolerated, with discharge occurring between postoperative days 4 and 7. None of the patients are braced. Activity is restricted to walking for the first 6 weeks after surgery, followed by light aerobic workouts on a treadmill or exercise bike until 6 months after surgery when the patients are released to full activity, if the spine fusion appears solid.

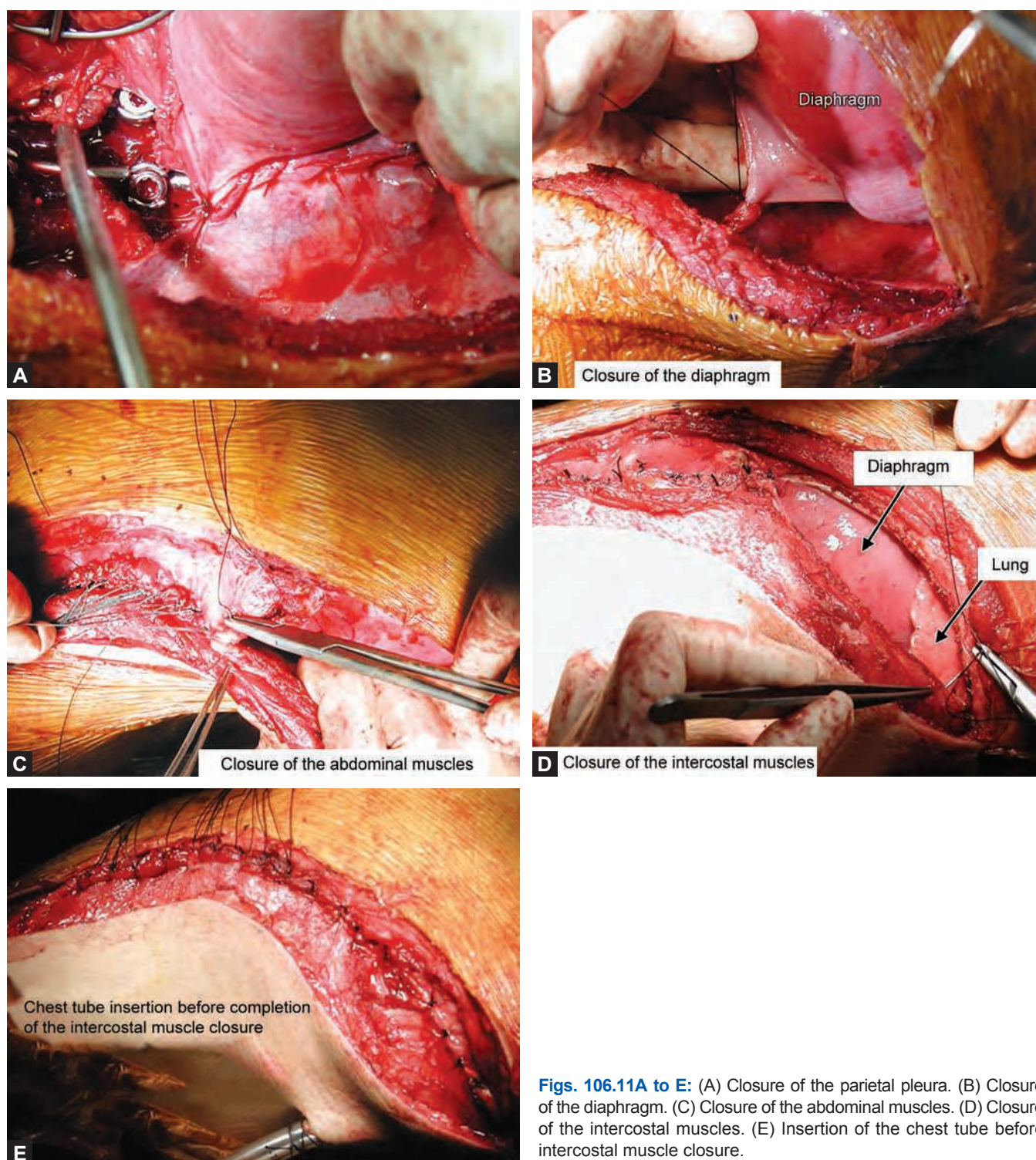
DISCUSSION

Deformity Correction

The average correction of TL/L curves varies from 70% to 80%.^{4,10} The correction depends on the curve flexibility, type of implant, reduction technique, and usage of cage. In general, outstanding correction can be achieved due to anterior discectomy and direct vertebral body derotation.

Single Rod versus Dual Rods

The benefits of the single rod include the ease and safety of single screw/rod placement to avoid the spinal canal and vascular structures. However, there are disadvantages of a single rod construct including an increased rod breakage rate and pseudarthrosis rate.^{3,5,11} A single rod is obviously less biomechanically stable, which will require bracing postoperatively in certain circumstances. Dual rods system is especially useful for larger patients or adults. As no restrictions are applied postoperatively, return to activities is quicker. It has advantage of satisfactory sagittal plane control. Dual rods have been the mainstay of treatment for scoliosis curves treated by an open procedure that allows



Figs. 106.11A to E: (A) Closure of the parietal pleura. (B) Closure of the diaphragm. (C) Closure of the abdominal muscles. (D) Closure of the intercostal muscles. (E) Insertion of the chest tube before intercostal muscle closure.

for increased biomechanical stability and an increased fusion rate.^{4,12,13} Disadvantages of the dual rod construct include difficulty in placing a dual staple and dual screws

in small patients with small vertebral bodies. However, a similar amount of radiographic deformity correction was obtained when compared to single-rod implants.¹³

Lung Function

There is concern regarding ultimate pulmonary function following open thoracotomy for anterior instrumentation and fusion procedures. Kim et al.¹⁴ showed the absolute values were unchanged but the percent predicted values were statistically less for those patients undergoing an anterior instrumentation and fusion for thoracic scoliosis curves via an open thoracotomy at 5 years postoperative. Kim et al.¹⁵ in another study demonstrated that an open thoracotomy approach for treating a main thoracic curve produces a significant decrease in the absolute pulmonary function tests values at 2 years postoperative while the thoracoabdominal approach for treating a TL/L curve did not. In addition to lung function, drawbacks related to thoracoabdominal approach are abdominal bulging, pleural effusion, ileus, and sympathectomy effect.

Pseudarthrosis

Pseudarthrosis rate seems higher with anterior-only surgery than posterior-only surgery. A single-screw/single-rod solid system reduced the pseudarthrosis rate comparing to a single-screw/single-threaded rod system. However, 6% ($n = 5$) of patients developed a pseudarthrosis with anterior single solid rod instrumented fusion for AIS.³ Common risk factors for pseudarthrosis were smoking, weight, and, for thoracic pseudarthrosis, hyperkyphosis $>40^\circ$ at T5–T12. Interestingly, SRS-22 questionnaire scores at the 2-year follow-up were not significantly different for those with pseudarthrosis versus those with a healed spinal fusion. Also, a broken single solid rod still showed apparent radiographic fusion in two of the four patients due to settling of the thoracic spine with an ultimate solid fusion with a slight increase in thoracic kyphosis postoperatively.¹⁰ Two-screw/two-rod system significantly reduces this pseudarthrosis rate.^{4,15}

Anterior Spinal Fusion versus Posterior Spinal Fusion

In comparison to posterior spinal instrumented fusion, anterior spinal instrumentation and fusion saves fusion levels by end vertebra to end vertebra.⁵ Significant rotational correction is possible by aggressive removal of anterior soft tissues. In skeletally immature patients, anterior fusion is chosen to avoid crankshaft phenomenon. It has

less chance of adjacent problem, as spinal extensor muscles are not disrupted. Sagittal plane realignment is possible by segmental compression or distraction of the disc space. Shufflebarger et al.¹⁶ showed excellent result by posterior-only approach on Lenke type 5 curve using selection of fusion level from upper end vertebrae to lower end vertebrae. Average coronal correction of the TL/L curves was from 52° to 10° (80%). In the sagittal plane, lumbar lordosis was normalized from 41° with a wide range (20° – 70°) to 42° with a normal range (34° – 47°). There were no pseudarthroses, no reoperations, no infections, no problems with screw placement, and excellent maintenance of correction at last follow-up. The LIV had 81% correction of coronal angulation; center sacral line to LIV was improved from 2.4 cm to 0.7 cm. Hee et al.¹⁷ showed that surgical correction of both the frontal and sagittal plane deformity are comparable to anterior instrumentation. Shorter lengths of surgery and hospital stay were the potential benefits of posterior surgery. Length of surgery was significantly shorter in the posterior group (189 minutes vs 272 minutes). Length of hospital stay was shorter in the posterior group (6.2 days vs 8 days). Estimated blood loss, duration of analgesia, and intensive care unit stay did not differ significantly between the two groups. Fusion levels were shorter in the anterior group (mean, 4.1 vs 5.0). Thoracolumbar sagittal alignment at T11–L2 was maintained for both groups throughout the follow-up period (Figs. 106.12A and B). The incidence of proximal junctional kyphosis was higher in the posterior group ($P < 0.01$).

Cobb-to-Cobb versus Very Short Segment Fusion versus Bone-on-Bone Technique

The Hall concept,⁸ a very short construct (three or four motion segments) with overcorrection of the apex, produced excellent coronal results. A high degree of flexibility is required for successful implementation of this approach. The candidate patient population is a relatively small proportion of patients with idiopathic lumbar or thoracolumbar scoliosis. Disc space wedging below LIV is always present due to the overcorrection of the deformity. In addition, a kyphosing effect over these segments is still an issue. Gaines et al.¹⁸ presented the technique and results achieved by limiting the instrumentation and fusion for idiopathic scoliosis $<75^\circ$ to only those vertebrae contained within the Cobb angle of the patient's scoliosis measured on the "stretch film." This allowed for



Figs. 106.12A and B: (A) SK is an 18+4-year-old female. She is very active and is dedicated professional dancer. Physical examination showed elevated right shoulder, asymmetric waist-line, and coronal decompression to the left. She had thoracolumbar (TL) idiopathic scoliosis classification Lenke 5CN. Preoperatively, the thoracic curve (T5-T10) was 38° and TL curve (T10-L3) was 55°. Isthmic spondylolisthesis was present at L5-S1. On side bending view, the lumbar curve was very flexible and corrected to 3° and the thoracic curve was corrected to 14°. Disc below L3 showed good flexibility with side benders. (B) She underwent an open anterior dual rod instrumentation and fusion from T11-L3 with anterior interbody structural support. Postoperatively, her TL curve was corrected to 20° with level shoulder with an excellent coronal and sagittal balance.

instrumentation one to four levels shorter than those used by Dr Kaneda. The instrumentation included roughly half the levels that would have been instrumented by traditional posterior segmental instrumentation. The preoperative thoracolumbar major curve was corrected from 50.5° to 18.3° (final) with fusion of four vertebrae, three discs. A spontaneous improvement of 37.4% occurred in the thoracic compensatory curve. The preoperative tilt angle improved from 27.7° to 8.3°. The sagittal and coronal balance was restored in all the patients. There were no neurologic, vascular, pulmonary, or implant-related complications. Union occurred within 3 months. All the patients returned to an unrestricted lifestyle within 4 months. Although short segment bone-on-bone instrumentation has reported good results, the placement of interbody cages at every level is recommended to maintain lumbar lordosis.¹⁹ The use of structural interbody support creates a fulcrum to increase curve correction when compression is applied to the convexity of the deformity. Biomechanical studies showed increased construct stiffness.²⁰

CONCLUSION

Anterior thoracolumbar and lumbar correction and fusion has been outstanding surgical approach to correct Lenke

type 5 or sometimes 6 curves with minimal fusion level from upper end to lower end vertebrae. Flexible cable and smaller rod has been replaced with dual rods to prevent pseudarthrosis and to support better stability. Bone-on-bone technique or bone graft without structural cage was known to have kyphogenic problem at thoracolumbar area. Cage insertion is strongly recommended to maintain lordosis in Lenke type 5. Very short segment fusion by overcorrection or bone-on-bone technique may have a limited role in small subset of patient population. Posterior approach showed many advantages over anterior approach such as faster operation time, more cosmetic, similar correction of deformity, and shorter hospital stay. However, we need more data on distal fusion level and proximal junctional kyphosis.

KEY POINTS

- Anterior thoracolumbar/lumbar (TL/L) correction and fusion is an outstanding surgical approach to correct Lenke type 5 or sometimes 6 curves with minimal fusion level from upper end to lower end vertebrae.
- Cage insertion is strongly recommended to maintain lordosis in Lenke type 5.
- Long anterior thoracoabdominal approach has drawbacks related to thoracoabdominal approach

are abdominal bulging, pleural effusion, ileus, deterioration of lung function, and sympathectomy.

- Very short segment fusion by overcorrection or bone-on-bone technique may have a limited role in small subset of patient population.
- More data on distal fusion level and proximal junctional kyphosis is needed to compare anterior approach with posterior pedicle screw technique.

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Short Segment 'Bone-on-Bone' Fusion for Adolescent Idiopathic Scoliosis

Robert W Gaines, Gregory Gebauer

Snapshot

- » Background
- » Patient Evaluation
- » Indications/Contraindications
- » Surgical Technique
- » Postoperative Care
- » Results
- » Complications

INTRODUCTION

The classification and treatment of adolescent idiopathic scoliosis (AIS) have evolved over the years. Initially most surgeries were performed using a posterior approach with a combination of hooks and rods used to correct the curvature and obtain a fusion. These initial systems were prone to high rates of pseudarthrosis and often failed to address sagittal imbalance.¹ Newer systems have been developed with the use of pedicle screw-based instrumentation that have been able to overcome many of these deficits; however, these surgeries still require the fusion of multiple levels to obtain proper balance and prevent curve progression.¹⁻⁴

While less familiar to most spine surgeons, in select patients an anterior fusion offers several advantages over posterior surgery. By removing the anterior disk, the curve can be more directly addressed and better correction can be achieved with fewer levels fused. Hypokyphosis, commonly seen in AIS, can also be addressed. Additionally, once the disc is removed, the endplates provide an excellent area of obtaining a fusion.

BACKGROUND

Flexible cable anterior implants and anterior interbody correction for idiopathic scoliosis was introduced by Dwyer, and modified by Zielke.⁵⁻⁷ Anterior surgery for

idiopathic scoliosis improved correction and demonstrated that keeping the number of fusion levels to a minimum was both possible and functionally important. However, while there were many good outcomes, rod breakage, screw pull-out, and nonunions were frequent. In addition, sagittal plane imbalance, or “flatback deformity”, was not fully addressed. The stiff single-rod used in the Texas Scottish Rite Hospital (TSRH) system was found to have similar disadvantages.⁸

In response to the deficiencies of the Dwyer, Zielke, and TSRH systems, a dual-rod anterior system was developed: the Kaneda Anterior Scoliosis System (KASS; Depuy AcroMed, Raynham, MA).⁹ Kaneda reported excellent results in patients with lumbar, thoracic, and thoracolumbar scoliosis.^{9,10} These results were replicated by several surgeons in the United States, and in other countries.^{11,12} The unique feature of this treatment paradigm was that the fusion and internal fixation was limited to those vertebrae contained within the structural major curve.

PATIENT EVALUATION

All patients should undergo a thorough history and physical examination. Any history of significant back pain or rapid curved progression should be identified. The patient should be asked about any family history of scoliosis. If the patient is female, the age at which menses started should be noted. Any family history of scoliosis should be



Fig. 107.1: A preoperative plan is based on the 'traction radiograph'. The patient is laid supine on the radiograph table on a 36-inch film. Two other individuals (assistants and/or family members) then 'stretch' the patient while the patient is instructed to relax. One provides forceful but non-violent traction to the patient's upper body (neck or shoulders) while the other provides the same to the legs.

identified. A complete neurological examination should be performed, including abdominal reflexes.

Appropriate imaging studies should then be obtained. Standing full length anteroposterior and lateral scoliosis views are obtained to assess curve magnitude, sagittal and coronal balance. If there are neurological abnormalities on examination or any concerning features seen on plain films (left thoracic curve, focal scoliosis, and congenital abnormalities), a magnetic resonance imaging should be obtained.

Once surgery is indicated, there are multiple techniques for assessing the flexibility of the curve. Most commonly bending or bolster films are obtained. These films are obtained by simply having the patient bend left or right having them lean over a foam bolster. Others have advocated the use of traction films (Figs. 107.1 and 107.2). Initially these were described as being performed while under anesthesia, with manual traction being applied to the ankles and shoulders while the patient is sedated. Others have suggested that the sedation is not necessary and gentle traction while the patient is awake is sufficient.¹³⁻¹⁸

Preoperative pulmonary function tests should be obtained when considering an anterior approach. If there are any abnormalities, consideration should be given to converting to a posterior approach.

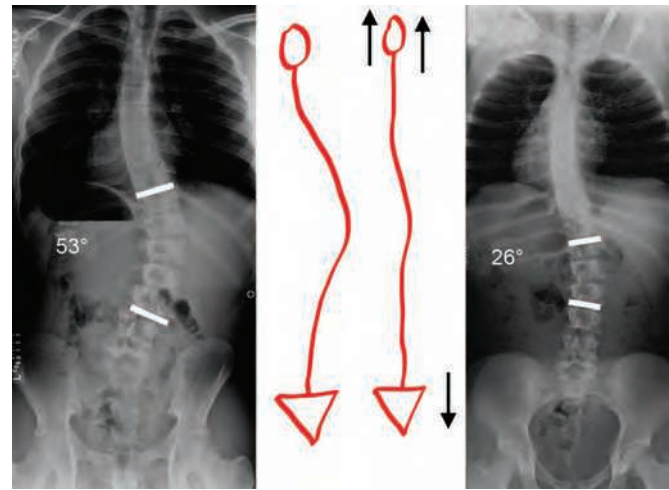


Fig. 107.2: An example of the 'stretch' radiograph. A type 5 curve measuring 53° on erect radiograph (left), 'stretched' out to 26° (right), based on the principle of a gentle stretch of the trunk (center).

■ INDICATIONS/CONTRAINDICATIONS

The Lenke classification system is currently the most commonly used system for AIS. Adolescent idiopathic scoliosis patients with Lenke I (thoracic main curve) and Lenke 5 (thoracolumbar curve) may be amenable to an anterior approach. The main curve should be <85° and the compensatory curves <50. The structural curve should correct to <50° on bending, traction, or stretch views. Limited use of this technique could be considered in patients with double or triple major curves; however, in generally, these would be best served by a posterior approach. When an anterior approach is used for patients with double or triple curves only the major curve should be corrected and the goal should be to balance the remaining curves. Patients should be approaching skeletal maturity and should be Risser stage 2 or greater (Table 107.1).

An anterior approach should be avoided in patients with neuromuscular scoliosis, impaired pulmonary function, extremely large curves (>85°), or in whom there are other contraindications to an anterior approach. In general, this approach should be avoided in skeletally immature patients (Risser <2) who have juvenile scoliosis (Table 107.2).

■ SURGICAL TECHNIQUE

Preoperative Planning

Once the appropriate films are obtained and the decision is made to proceed with an anterior approach, a surgical

Table 107.1: Indications for anterior short segment fusion.

1. Idiopathic scoliosis
2. Single major curves (Lenke types 1 and 5)
3. Major curve with Cobb measurement < 85°; thoracic modifier N or -.
4. Major and compensatory curves 50% flexible or reduce to 30° on 'stretch film'
5. Risser sign > 2

Table 107.2: Contraindications for anterior short segment fusion.

1. Abnormal preoperative pulmonary function tests
2. Infantile and Juvenile idiopathic scoliosis.
3. Most neuromuscular scoliosis
4. Many double major curves, proximal thoracic structural curves
5. Large (>85), stiff curves (less than 50%) flexible on the 'stretch film'
6. Risser < 2

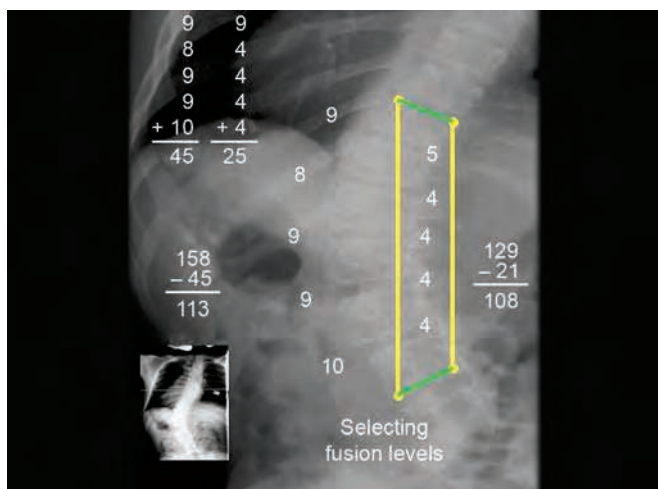


Fig. 107.3: An example of a preoperative blue print: The fusion levels are determined using the stretch radiographs. The Cobb levels are identified on the stretch radiograph. The convex (158 cm) and the concave (129 cm) chord lengths are determined from the respective corners of the Cobb vertebrae. The individual disc heights are added on the concave (21 cm) and the convex sides (45 cm). Subtracting the disc heights from the corresponding chord lengths gives us the measure for the corrected heights of the convex and the concave columns. A value <5 mm between the convex and the concave sides would lead to a satisfactory correction as shown diagrammatically.

plan is developed. This is based on the bending or traction films (Fig. 107.3). The Cobb levels are identified. The cords length on the convex side is obtained by measuring the length from the superior corner of the cephalad vertebra in the Cobb to the inferior corner of the caudal vertebrae. The individual disc heights on the convex side are then measured and added together. This number is then subtracted from the cord length on the convex side. The same process is then repeated on the concave side. The difference between the numbers on the concave and convex sides should be within 5 mm. If the difference is >5 mm additional levels may need to be included.



Fig. 107.4: Positioning the patient in the right lateral decubitus position on a peg board. This secures the patient throughout the procedure.

Positioning and Exposure

The patient is first positioned on a peg-board on a radio-lucent operating table (Fig. 107.4). Neuromonitoring, including baseline somatosensory-evoked potentials and motor-evoked potentials should be established. For constructs that will end to T11 or below, an extrapleural, retro-peritoneal exposure is performed. The 11th and/or 12th rib may be removed to help with exposure. A thoracotomy is performed when the instrumentation is going to extend more proximally. At each level, the segmental vessels are isolated, ligated twice with vascular clips and then transected. The levels that are to be instrumented are then exposed including the transverse processes and rib heads. The rib heads at the appropriate thoracic levels are then removed. An osteotomy is created through the neck of the rib between the costotransverse and costovertebral joints. Removing the rib-head exposes the costovertebral joint and the neural foramen. The remaining peripheral rib articulates at the costotransverse joint.

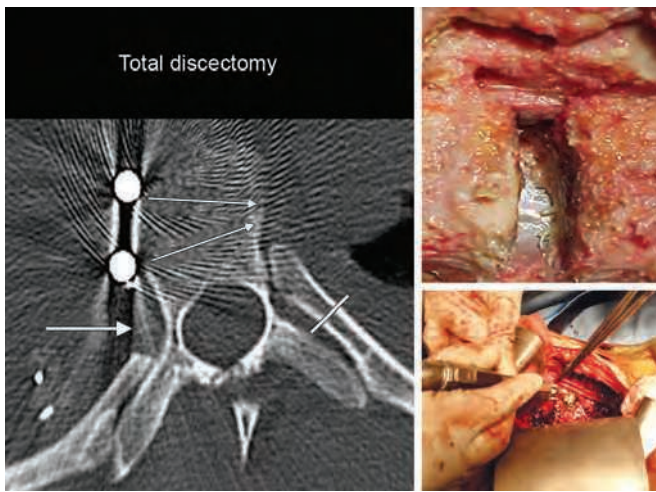


Fig. 107.5: Excision of the rib head (right bottom) allows for a safe identification of the posterior extent of the disc, and safe placement of the instrumentation (left). Performing a “total discectomy” at each level in the apical levels of the curve (right top) is central to the success of this procedure.

The neural foramen is then identified. Precise awareness of the location of the foramen is essential, as it guides the surgeon to the spinal canal and protects the neural structures. A curved curette is used to carefully expose the foramen. Once adequately exposed, a Penfield dissector is placed into the spinal canal through the intervertebral foramen and anterior to the spinal cord. The posterior aspect of the intervertebral disc is palpated. This identifies the posterior annulus, and confirms the interval between the posterior annulus of the involved vertebra and the thecal sac. Epidural bleeding is controlled by thrombin-soaked gel foam, applied through the foramen.

Thoracic Discectomy and Endplate Preparation: The Bone-on-Bone Technique

The intervertebral discs are then resected at the levels determined in the preoperative plan. The discectomy should be performed at the most apical level first and then continued to the caudal and cephalad levels. This approach permits better visualization of the more peripheral discs with increasing correction. In general, the straighter the spine, the easier the disc space is to visualize and the more straight-forward the discectomy. The disc material can be removed using Cobb's, curettes, pituitaries, and rongeurs. All the disc tissue must be removed until the two vertebrae begin to collapse toward one another. On the concave side, the posterolateral corner on the contralateral side and the posterior annulus (and

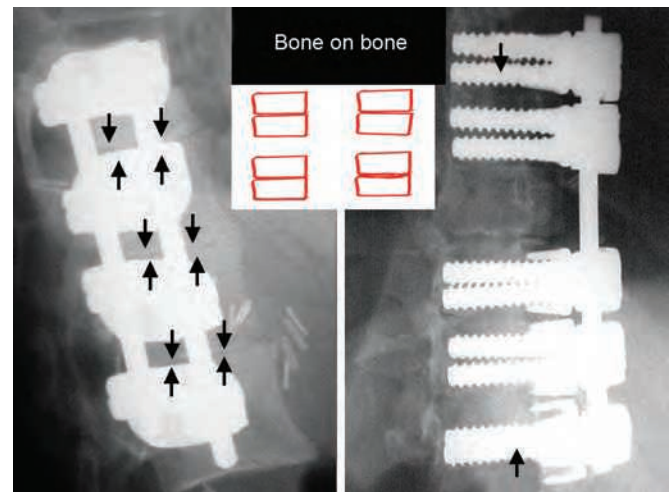
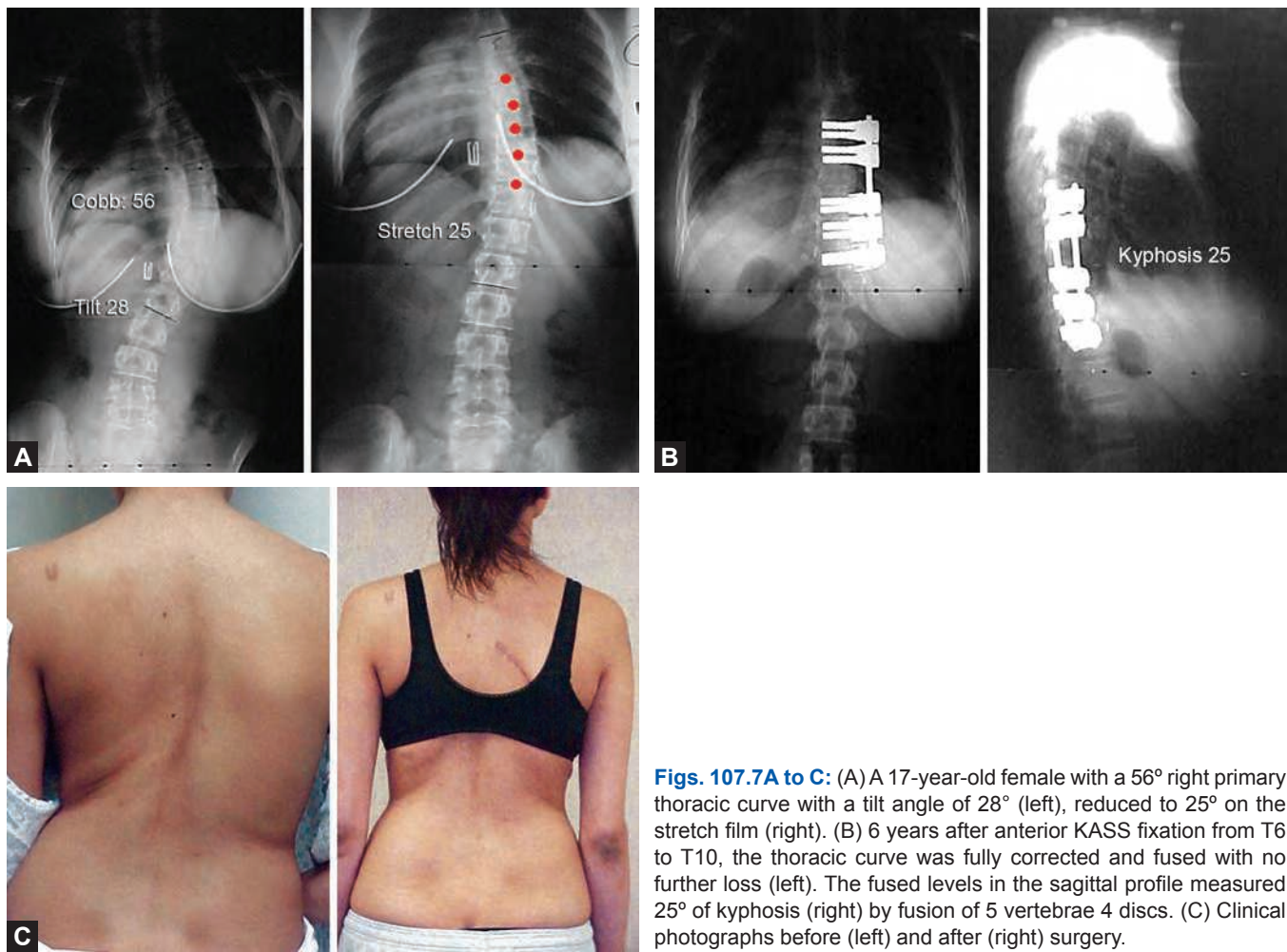


Fig. 107.6: A complete discectomy is followed by bone-on-bone apposition. This corrects the deformity in all three planes. The end plate apposition is demonstrated. Bone-on-bone inter-body contact leads to a favorable position for the fusion.

the posterior longitudinal ligament) must be removed using Kerrison rongeur or a sharp straight long-handled rongeur. The cartilaginous endplates are removed while the bony endplates are left intact. If necessary a small portion of the peripheral endplate on ipsilateral side can be removed to allow for better visualization. If there are voids in the endplates auto or allograft chips can be used to fill them. Once the interspace closes with good bone-on-bone apposition, gel foam is placed into the disc space to help decrease bleeding. Attention is then turned to the next disc space (Figs. 107.5 and 107.6).

After all the discs are excised, a “repositioning maneuver” is performed. This is done by stretching the patient, while the anesthesiologist or an unscrubbed assistant lifting the torso and gently pulling the lower shoulder upward. This may help with curve reduction.

An appropriate sized vertebral body staple is then selected and placed in the center of the vertebral bodies over the segment of the spine to be instrumented. Fluoroscopic imaging is then used to assess the coronal plane correction of the major curve; the positioning of the vertebral body staples; the correction of the tilt angle; and sagittal plane correction. Any adjustment regarding selection of fusion levels is made at this time. Perfect placement of the staples is essential for proper screw placement. The staples function as a “screw-guide”. Two triangulated vertebral body screws then provide a stable vertebra-implant interface. The screws should have bicortical purchase, especially the screws at the ends of the construct.



Figs. 107.7A to C: (A) A 17-year-old female with a 56° right primary thoracic curve with a tilt angle of 28° (left), reduced to 25° on the stretch film (right). (B) 6 years after anterior KASS fixation from T6 to T10, the thoracic curve was fully corrected and fused with no further loss (left). The fused levels in the sagittal profile measured 25° of kyphosis (right) by fusion of 5 vertebrae 4 discs. (C) Clinical photographs before (left) and after (right) surgery.

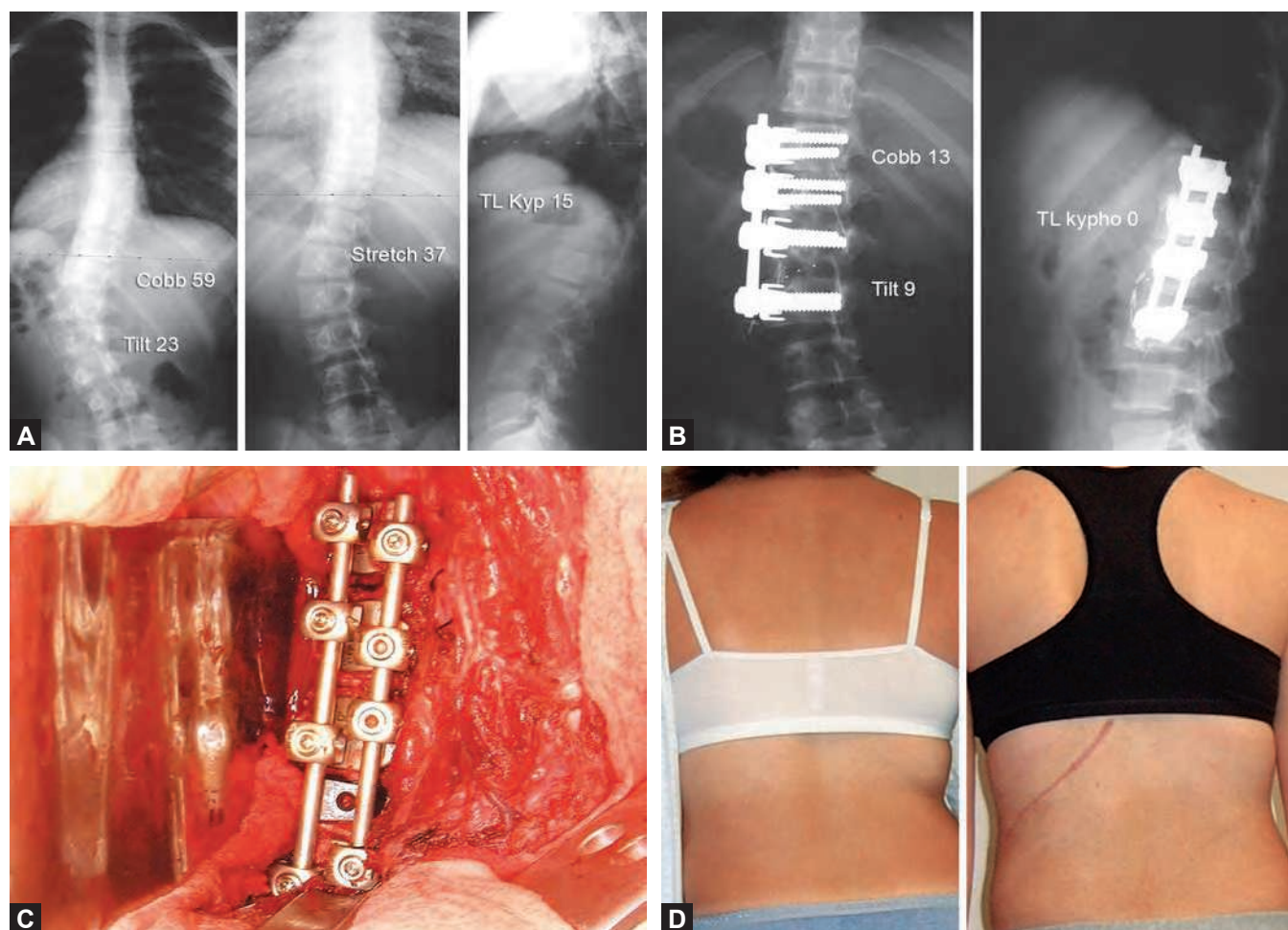
Once the screws are properly placed, an assessment is made about the length and contour of rods necessary to both correct the curve and also restore ideal sagittal plane alignment. Once that assessment is made, the rods are selected and bent if necessary. The first rod is placed into the screws and secured with caps. At each level a compressor is used to bring the peripheral vertebrae toward the apex. A Penfield dissector is used to palpate between the adjacent vertebrae to ensure that bone-on-bone apposition is being achieved. The second rod is then inserted into the second set of screws. No additional correction is achieved with the second rod and it is used primarily to improve rotational stability.

Clinical examples of both coronal and sagittal plane correction appear in Figures 107.7 to 107.10.

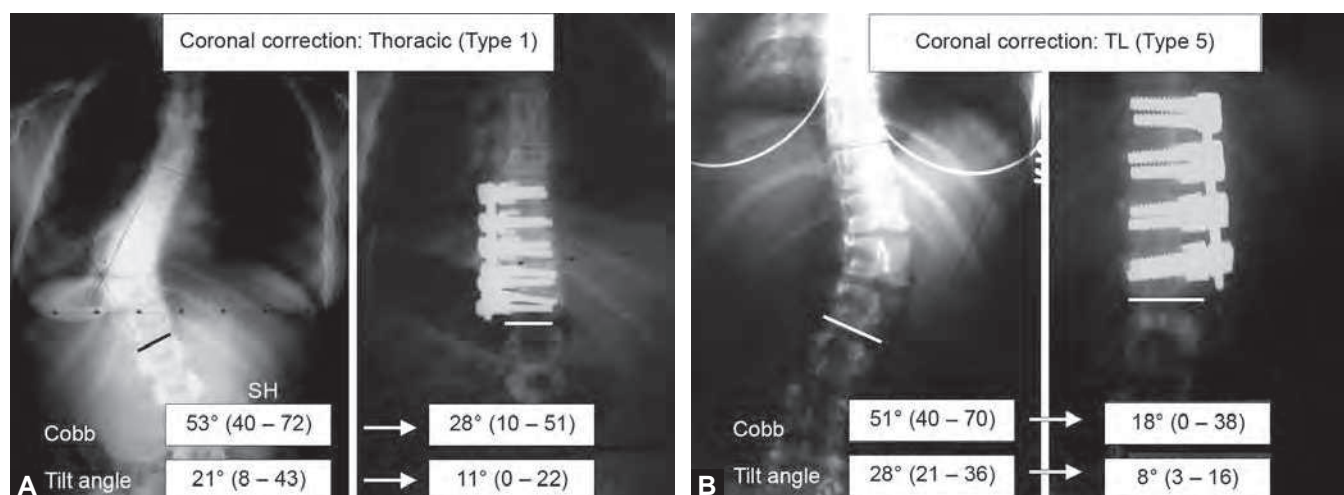
For Lenke type 5 curves that extend below T11, interbody cages may be used to help restore lordosis. The intraoperative assessment of the sagittal profile—by both clinical

inspection and intraoperative X-ray or fluoroscopic imaging guides the need for cages. These cages are inserted using a standard technique for lateral interbody cages. Bone graft, either iliac crest or allograft should be placed in the cages. The screw/rod construct should include all levels into which lateral interbody cages have been placed as well as all of the proximal levels where the bone-on-bone discectomy has been performed.

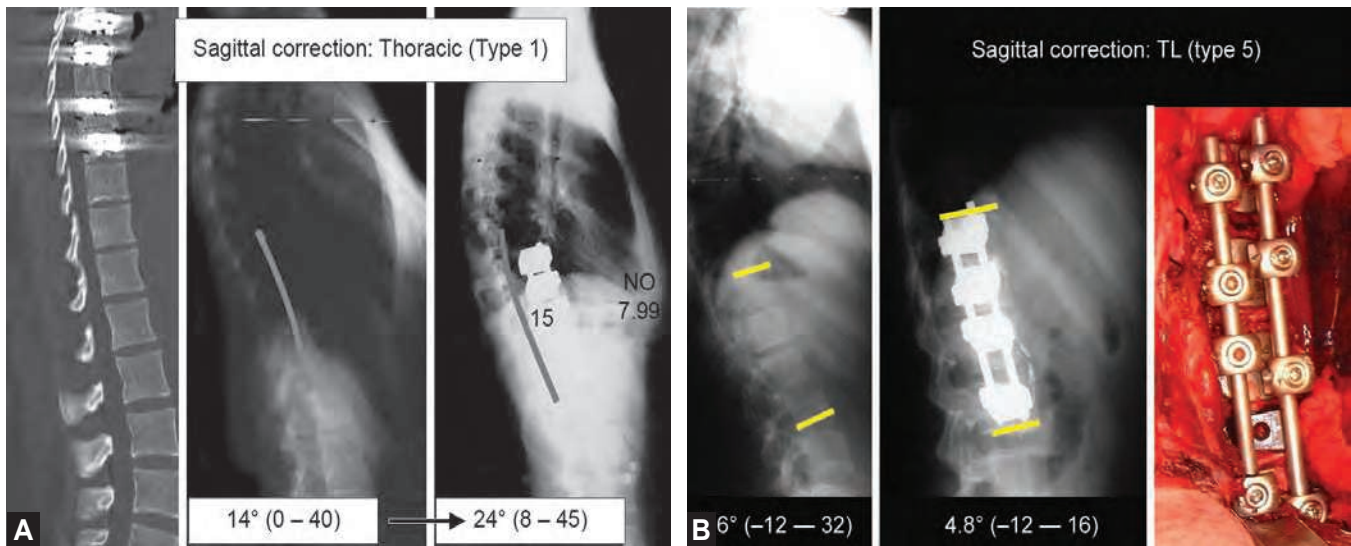
At the completion of the case, an epidural catheter can be placed into the intervertebral foramen at the top of the construct to help provide postoperative analgesia.¹⁹ For cases involving a thoracotomy, the parietal pleura or a Gore-Tex pericardial patch is then sutured over the rods and screws to serve as a barrier between the instrumentation and the lungs. A chest tube is also placed and set to suction. Routine muscle and skin closure is then performed. If thoracolumbar instrumentation is performed with the extrapleural-retroperitoneal approach, no chest drain or other drain is necessary (Table 107.3).



Figs. 107.8A to D: (A) A 19-year-old female with a 59° type 5 curve with a tilt angle of 23° (left) with a thoracolumbar junctional kyphosis measuring 15° (right), stretching to 37° (center). (B) This was corrected by T12 – L3 instrumentation and discectomy to a Cobb of 13° and a tilt angle of 9°. The thoracolumbar junctional kyphosis was corrected by placing a cage at L23, and a bone on bone apposition at the other levels. (C) Intraoperative picture after the correction and instrumentation. (D) Clinical photographs before (left) and after (right) surgery.



Figs. 107.9A and B: The results of coronal correction of type 1 curve (A) and type 5 curves (B).



Figs. 107.10A and B: The results of the sagittal correction of type 1 curve (A) and type 5 curves (B)

Table 107.3: Tips and tricks for short segment fusion for scoliosis.

1. Patient must be securely placed in lateral position on a peg board or similar table
2. If the proximal instrumented level is below T11, an extra-pleural retroperitoneal approach can be performed
3. If a transpleural approach must be performed, there is no need to deflate the lung. Careful retraction is enough for a wide operative field
4. The foramen must be identified in order to excise the posterior annulus. This allows the vertebrae to collapse one toward the other, with a bone on bone apposition
5. The discectomies proceed from the apical disc toward the ends of the curve to facilitate exposure of the more peripheral discs.
6. Although the authors prefer a dual rod system, this technique does not rely on the implant for success. BONE ON BONE—following “total discectomy” at each operated level is the key factor.
7. BMP, allografts or bone substitutes are not required with the bone-on-bone technique.
8. Thoracolumbar curves (Lenke type 5) may require the placement of a cage below T11 to assure anatomic reconstruction of the sagittal profile.

POSTOPERATIVE CARE

Following surgery patients are generally kept in the intensive care unit. Depending on the patient and the facility, this may be for as little as 24 hours or up to 4–5 days. If placed during surgery, the epidural catheter can be used for pain control. This is weaned by the 3rd or 4th day after surgery. If no epidural catheter was placed, then a patient-controlled analgesia pump with intravenous pain medications is used. Patients are gradually transitioned to oral pain medicines. The chest tube is first placed to suction and then to waterseal. Serial chest X-rays are taken to ensure that no pneumothorax develops. If there is no

pneumothorax while on waterseal, the tube can be discontinued, generally by the 3rd or 4th day postoperatively.

Early ambulation and mobilization are encouraged. Patients should be out of bed within 24–48 hours of surgery. Generally back braces are not necessary although a corset style brace may provide some pain relief. A more rigid brace can be used at the surgeon's discretion or if there were any concerns about fixation during the surgery.

After discharge from the hospital, the first month following surgery is focused on rest and allowing time for healing. Physical rehabilitation proceeds after the first month to restore the patient to his or her usual activities. School children are back in school by 6–12 weeks following

the surgery, and working adults are back to work, at least part-time, within 6–8 weeks.

RESULTS

Initial reports on the outcomes of selective anterior fusion were concerning. Bernstein and Hall²⁰ reported on a series of 17 patients with thoracic curves, all had excellent curve correction (87%) that declined slightly at 24 months (67%). During surgery three patients had problems with placement of the instrumentation that required additional levels to be fused. There were no reported pseudarthrosis or instrumentation failures.

Betz et al.¹ reported on a larger series of 178 patients with primary thoracic curves, 100 of whom were treated with posterior fusion and 78 with anterior surgery. They found similar correction of coronal curves (58% for posterior vs. 59% for anterior). Anterior surgery was better able to address hypokyphosis (81% of patients with hypokyphosis were corrected to within 20°–40° compared to only 19% with posterior surgery). Hyperkyphosis however was much more prevalent after anterior surgery, occurring 40% of the time when preoperative kyphosis was ≥20°. An average of 2.5 fewer levels were fused using an anterior approach; however, higher rates of complications were also reported in this group. Patients treated with an anterior approach had higher rates of pseudarthrosis (5% vs. 1% in the posterior group), loss of correction (23% vs. 12%), and implant breakage (31% vs. 1%). The anterior procedures utilized a flexible rod system, which explain the higher rates of implant-related complications, pseudarthrosis, and loss of correction seen in this study.

Later studies demonstrated better results. Smith et al.²¹ reported on a series of 15 patients followed radiographically for an average of 44 months and clinically for 61 months. They reported a 66% correction of the major thoracic curve and 40% and 61% spontaneous improvements in proximal and distal curves, respectively. They noted no change in sagittal alignment. At final follow-up, they reported a modified Social Responsiveness Scale (SRS) score of 4.3 out of 5 (average of all five domains). They also reported an overall patient satisfaction rate of 88%. There were no cases of pseudarthrosis or implant failure. Two patients developed adjacent segment disease below the fusion resulting in spinal stenosis and radiculopathy. One patient developed proximal degeneration. Additional studies continued to show good curve correction for tho-

racic curves (47–71%) with a relative low rate pseudarthrosis and implant-related complications.^{9,10,12–14,22,23}

Several studies have also directly compared anterior and posterior fusion techniques. Muschik et al.²⁴ directly compared patients undergoing anterior and posterior approaches. In their series, 104 patients underwent posterior fusion for AIS and 37 were treated with an anterior approach. All patients had primary single thoracic curves. They noted similar correction of the coronal curves and hypokyphosis (T4–T12 <20°). For patients with hyperkyphosis (T4–T12 >40°), a posterior approach was able to achieve some correction while less correction was seen in anterior surgery; however, the difference between the correction from the two approaches did not reach statistical significance. There was an equal rate of complications between the two groups (approximately 12%). Importantly, they did note that anterior surgery requires four fewer segments to be fused.

The efficacy of anterior fusion for thoracolumbar curves has also been studied. Bitan et al.²⁵ reported on a small series of 24 patients with thoracolumbar curves treated with anterior surgery. Five of these patients had Harms cages placed into the intervertebral space. They reported a 59% correction of the lumbar curve and a 21% correction of the compensatory curve. On an average 2.9 levels were fused. Two patients were noted to have a pseudarthrosis, and one had a loss of fixation. These are similar to the results seen by Kusakabe et al.¹⁴ who reported a 64% correction in Lenke V curves treated with anterior fusion. They also noted a 37.4% spontaneous correction of the thoracic curve.

Geck et al.²⁶ compared 62 patients with Lenke V curves, half were treated with and anterior surgery and the remainder using a posterior approach. They noted significantly better results from posterior surgery, including better initial curve correction (84% vs. 67%), less loss of correction over time (3.4% vs. 9.4%), better correction of lumbar lordosis (17% vs. 0), and shorter average hospital stay.

The long-term outcome following anterior fusion of Lenke V curves was reported by Sudo et al.^{27,28} They followed 30 patients for a mean of 17.2 years. They reported a 79.8% correction with 3.4% lost over time. Twenty-three percent of patients were noted to have degenerative changes at the levels above the fusion. Two patients required extension of the fusion, one for thoracic curve progression and one for disc wedging. At follow-up, the mean SRS-30 was 4.2 when averaged overall five domains.

COMPLICATIONS

Many of the complications reported after anterior surgery for scoliosis are similar to those for any major surgery and include ileus, urinary tract infection, surgical site infections, misplaced hardware, and wound healing issues.^{1,14,20-22} Additional complications have been reported related to patient positioning. Betz et al. reported skin breakdown from an axillary roll, while Seraph et al. had one case of brachial plexopathy.

Hardware failure and pseudarthrosis were more commonly seen in earlier studies. Intraoperative hardware failure has been reported and has led to additional levels needing to be fused.^{20,24} Late hardware failure may be associated with pseudarthrosis. Rates of pseudarthrosis range from 0% to 5%.^{1,14,23} Sweet theorized that risk factors for pseudarthrosis include smoking, weight >70 kg, and hyperkyphosis.

Major vascular injuries have not been reported; however, Betz did report of an injury to a segmental vessel that required reoperation.¹ Segmental vessels are of particular concern as they provide the blood supply to the spinal cord. The largest of these vessels, the artery of Adamkiewicz, generally originates on the left side between T9 and T11. Disruption of this artery or even some of the smaller segmental vessels may affect the blood supply to the spinal cord. This is a relatively rare event (1.1% of anterior surgeries²⁹), but can be potentially devastating. It has been theorized that patients with hyperkyphosis, intraspinal anomalies, or who are undergoing revision surgery may be at higher risk. The artery can be temporarily occluded to see if there are any changes in neuromonitoring. If there are no changes, it can be assumed that the artery is safe to ligate.

In addition, there have been reports of approach related complications. Thoracolumbar approaches put at risk the lumbar plexus, genitofemoral nerve, and sympathetic chain. Brodner et al. reported on a series of patients undergoing surgery for both thoracic and thoracolumbar curves.¹³ Of the 11 patients treated for thoracolumbar curves, they noted four cases of anterior thigh numbness that they attributed to retraction of on the ilioinguinal and/or genitofemoral nerves during the procedure. They also noted five cases of what was termed a "sympathectomy effect" following the surgery, which they described as being a "nuisance" only and did not require any further intervention.

Anterior surgery for thoracic curves invariably involves disrupting the pleural cavity and the associated

risks. Commonly reported complications include pneumothorax and pleural effusions.^{1,20,24} Patients with scoliosis are already predisposed to decreased pulmonary function and anterior surgery may exacerbate this. Kim et al.³⁰ have evaluated the effect of spinal fusion on pulmonary function in patients with scoliosis. They noted significant decreases in forced expiratory volume in 1s (FEV1) and percentage predicted forced vital capacity (FVC) in patients who had anterior surgery at 5 years. Patients with posterior-only surgery had a slight increase in FEV1 and no change in FVC. Lonner et al.³¹ noted similar decreases with anterior procedures and found greater changes in patients undergoing open thoracotomy as opposed to thoracoscopic procedures. Newton et al.³² predicted that 50% of patients undergoing an open thoracotomy will have a 15% or greater decrease in their pulmonary function at 2 years. In contradiction to these studies, Verma et al.³³ noted only minimal changes in pulmonary function at 2-year that did not vary significantly between anterior, posterior, or thoracoscopic approaches.

SUMMARY

Short segment anterior fusion provides a safe and effective option for the treatment of selective patients with AIS. Careful patient selection is essential. Eligible patients should have Lenke I or V type curves measuring <85°, with secondary curves <50°. Consideration should also be given to sagittal balance. While anterior surgery may help correct the hypokyphosis commonly seen in patients with AIS, it may accentuate hyperlordosis and should be used with care in these patients. Careful preoperative planning is essential and bending or traction films should be utilized to select the levels to be included in the fusion. Initial surgeries were complicated by relatively high rates of implant failure and pseudarthrosis; however, this has decreased with newer surgical techniques and implant designs. While the surgery remains technically demanding, studies have shown excellent long-term results with fewer levels fused compared to comparable posterior surgery and a similar rate of complications.

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Spondylolysis and Spondylolisthesis in Children

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Snapshot

- » Epidemiology
- » Pathogenesis
- » Classifications
- » Clinical Presentation
- » Treatment
- » Case Examples

INTRODUCTION

Spondylolysis and spondylolisthesis (SL) are reported to be the most common causes of structural low back pain in children and adolescents.¹ Spondylolisthesis is defined as the anterior translation of one vertebra over another, most commonly involving the lumbosacral junction. “*Spondylos*” is the Greek word for vertebra, and “*listhesis*” means to slip or slide. This deformity frequently originates from stress fractures, or small cracks, in the pars interarticularis (pars). These stress fractures often result in spondylolysis, which is a defect of the vertebral arch, specifically the pars. With a weakening of this posterior buttress, there is greater tendency for the vertebra to sublux out of place. Wiltse et al. originally described six major classifications of spondylolysis based on etiology, identifying congenital or dysplastic (involving dysplasia present at birth), isthmic (pars stress fracture or instability), degenerative (arthritic), traumatic, pathologic (tumor or infection), and postsurgical.² Isthmic is the most common variety of SL in the skeletally immature patients. Regardless of the etiology, the condition often progresses to a final common pathway: forward slippage of one vertebra on the one subjacent.³

Spondylolysis leading to SL often occurs during the first and second decades of life. The majority of patients with spondylolysis and SL are pain free, and therefore

are unaware of their condition. Symptomatic adolescents typically present with associated lower back pain and weakness or numbness, depending on which spinal nerves have been affected. No major progression of the disease is generally seen after this period; however, in middle age degenerative SL becomes more prevalent. The quality of life in patients with spondylolysis and those with low-grade slips is comparable to that in the normal population, whereas high-grade listhesis tends to progress and can cause disability in a relatively higher proportion.³

Knowledge of the natural history of the disease may help when determining treatment options. Conservative management is generally the standard of care for low-grade subluxation, with surgical treatment reserved for high-grade SL.

EPIDEMIOLOGY

The incidence of SL in children has been reported by Fredrickson et al. to be ~4%, increasing to 6% in adulthood.⁴ Hensinger examined ethnic differences, finding that the incidence in Caucasian males is higher than that among black females; however, high-grade listhesis occurs four times more frequently in females than in males.⁵ Rowe and Roche explored the variance of SL in demographic groups, finding an incidence of 6.4% in white males, 2.8% in black males, 2.3% in white females, and 1.1% in black females.⁶

Other studies have similarly found incidence disparities between ethnicities; at an extreme, spondylolysis rates as high as 54% can be found among certain Eskimo populations.⁷ Differences in rates of SL based on location have also been observed, with 82% occurrence of SL at L5–S1, 11.3% at L4–L5, 0.5% at L3–L4, and <0.5% at L2–L3.⁶

Beutler et al. followed a cohort of 500 patients for 45 years to help define disease history.⁸ By age 6, 22 patients were diagnosed with SL or spondylolysis. After a 45-year follow-up, a total of 30 patients, or 6% of the total studied population, had pars lesions. Their results suggest that the clinical course of the pathology is typically benign, and that the subluxation is mostly stable; after 20 years, progression was seen in <40% of patients with a listhesis. There was no correlation between pars defects and pain, and only 15% of individuals with a pars defect developed SL. Additionally, none of the patients with unilateral pars defects developed listhesis. Many patients, including some with high-grade slips, were asymptomatic, and the authors concluded that the disease may be largely underreported due to the lack of symptoms. Patients with low-grade SL have a lower rate of progression compared to those with a higher-grade slip. Patients who have a higher grade of SL as well as greater lumbosacral kyphosis and higher slip angle were also found to have a higher risk of progression.^{9–11} In an archeological and anatomic study of two different ethnic groups (Aleut and Arikara Plains Indians), Whitesides et al. found a higher frequency of spondylolytic SL with decreased sacral table angle in homogenized groups, which suggests a genetic component to SL etiology.¹²

Adult progression of SL is most closely related to degenerative changes in the intervertebral disc. As degeneration progresses and the disc space collapses, symptoms may develop associated with advancing listhesis. However, symptoms are not always associated with disease progression. Floman reviewed 18 patients with known asymptomatic SL who developed severe symptoms due to disc degeneration at the level of the slip, and found progression of subluxation to range from 9% to 30% in affected patients.¹³ In a retrospective long-term study of surgically and conservatively treated patients, Seitsalo et al. found an association between the natural history of SL and degenerative changes; the magnitude of listhesis was positively correlated to the degree of disc degeneration in the olisthetic segment. This group also found a correlation between the number of degenerated discs or the degree of degenerative disc disease and low back pain symptoms.¹⁴

However, spontaneous stabilization of the olisthetic segment was observed in the majority of the patients, leading the authors to speculate that the natural history of SL is benign.¹⁴ In a review of adult spondylolytic and SL patients in Finland, Virta found that 33% of patients progressed to >10% slip, although no correlation of these findings with symptomatic low back pain was observed.¹⁵

After a cross-sectional review of 4,151 patients from the Copenhagen Osteoarthritis Study Group, Sonne-Holm et al. determined that spondylolysis may proceed to SL in adulthood. Notable risk factors for this progression included increased age and higher body mass index (BMI) in women, and increased lumbar lordosis and decreased pelvic inclination. In men, lumbar SL was associated with higher BMI and increased lumbar lordosis, but not aging. Pelvic inclination and lordotic angle were found to be individual risk factors for lumbar spondylolysis.¹⁶

Sports and other activities undoubtedly can cause or further progression of SL in some patients, increasing the incidence from the 6% to 8% rate seen in the normal population. Much higher rates have been observed among individuals who participate in high-impact sports, including gymnastics, rowing, and football.¹⁷

■ PATHOGENESIS

A wide variety of pathological processes may result in an abnormal lumbosacral junction. The etiology of many of these pathologies is still not well understood, and is currently a matter of debate and study. Various classifications have attempted to discriminate between these etiological processes, to help determine optimal treatment strategies. As previously described, associated risk factors for slip progression in the immature spine include the following:

- Female gender
- Presentation at younger age
- Severity of slip at presentation
- Dysplastic type (congenital dysplasia of the sacrum or L5 vertebral arch)¹⁸
- Increased slip angle or lumbosacral angle.

The slip angle and lumbosacral angle have been evaluated by Dubousset, who concluded that these angles were the most accurate predictors of disease progression.¹⁹ Marchetti and Bartolozzi aimed to classify disease based on etiology, concluding that dysplastic bony structures may be the cause of a more aggressive and evolving type of deformity.²⁰ Pawar et al. studied 131 patients with developmental SL, and found that in the normal population,

88% had no or mild dysplasia, while most patients with low-grade (62%) or high-grade (73%) SL had moderate or severe dysplasia, respectively.²¹ This report further described six criteria for assessing dysplasia.²¹ In 2005, Herman and Pizzutillo added to the Marchetti-Bartolozzi classification, categorizing developmental SL as old pars fractures.²² Pizzutillo also studied the patients and families with SL, and noted a hereditary component in 28% of cases, which was often found incidentally. In this group of 70 patients and 222 first-degree relatives, isthmic defects were consistently more frequent than the dysplastic variants.²³

In the last decade, several papers described a variety of spinopelvic parameters, with associated etiological importance to developmental SL.²⁴⁻²⁶ In many reports, pelvic incidence was observed to be higher in spondylolisthetic patients. Since pelvic incidence is a specific, non-variable parameter unique to the individual, a high pelvic incidence correlates with a high sacral slope, thus increasing shear forces through the lumbosacral junction. While sacral slope may gradually increase for Meyerding grades 1, 2, and 3, it was observed to decrease in grades 4 and 5.²⁷ Vialle et al. surmised that this phenomenon was due to diminishing contact with the sacral endplate leading to sacral and pelvic retroversion.²⁷ Vialle et al. also observed that SL patients in general have increased sacral slope, pelvic tilt, and lumbar lordosis as well as a decreased thoracic kyphosis, concluding that the lordosis was secondary to the high pelvic incidence and therefore related to high shear forces in the pars.²⁷ A rounded sacral dome also predisposes to progression of slip in the presence of a lumbosacral deformity. Additional research involving radiographic parameters is recommended to better define the significance of these factors, specifically in defining prognosis. Thus, this spinopelvic parameters seem to have strong correlation with clinical and surgical outcomes.

CLASSIFICATIONS

This complex group of pathologies has been classified both by anatomical characteristics (Meyerding and Wiltse) and by etiology (Marchetti and Bartolozzi).^{2,20,28,29} The Meyerding classification is based on the degree of displacement of the superior vertebra over the inferior segment as visualized in a lateral radiograph. Grade 1 is defined as <25% displacement, grade 2 from 26% to 50%, grade 3 from 51% to 75%, and grade 4 from 76% to 99%. Although 5, is not part of the original classification system, it is reserved for the complete slippage of the upper vertebrae; Spondyloptosis.

Table 108.1: Wiltse-Newman anatomic classification, recently updated with a type VI.

Wiltse-Newman spondylolysis classification

Type I	<i>Dysplastic</i>	Olisthesis due to congenital defect
Type II	<i>Isthmic</i>	Pars interarticularis lesion, due to stress fracture (subtype A), elongated and intact pars (B) or acute fracture (C)
Type III	<i>Degenerative</i>	Chronic intersegmental instability
Type IV	<i>Traumatic</i>	Injury causing fracture in areas beyond the pars
Type V	<i>Pathological</i>	Olisthesis due to bone disease
Type VI	<i>Iatrogenic</i>	Post-surgical

The Wiltse classification divides SL into five types, with type II often divided into subtypes based on the acuity of the pars lesion. The dysplastic type involves congenital dysplasia in the sacrum or L5 vertebra. In isthmic SL, the basic lesion is a pars defect, differentiated as intact, elongated, or fractured/lysed. Type III is characterized as degenerative, and types IV and V are from traumatic and pathological etiologies, respectively (Table 108.1). A type VI category was later added, referring to an iatrogenic (postsurgical) etiology.²

The Marchetti classification distinguishes between developmental and acquired types. Developmental type is divided into low- and high-grade dysplasia, although the differentiation between these dysplastic types is unclear. Acquired SL is secondary to trauma, surgery, pathologic disease, or degenerative processes. The traumatic form is due to acute injury or stress fracture. Stress fractures are often sports related, and may be distinguishable from developmental etiology by the absence of dysplastic changes (Table 108.2 and Fig. 108.1).²⁰

In 2005, Herman and Pizzutillo proposed a new classification specifically for the pediatric population, combining the Wiltse and Marchetti systems.²² The authors proposed that dysplastic be considered one category, and that type II (developmental) refer to a child that was diagnosed incidentally and secondary to a pars defect, excluding primary defects. The traumatic category was divided into acute and chronic fractures; the latter included a pars stress reaction, stress fracture, or spondylytic defect. The final classification, type IV, was pathological. Reliable treatment algorithms have been based on this combined algorithm, with type I patients typically receiving strict

Table 108.2: Marchetti classification based on etiology.

Marchetti-Bartolozzi spondylolysis classification

Developmental	High dysplastic: lysis, elongation Low dysplastic: lysis, elongation
Acquired	Traumatic: acute fracture, stress fracture Pathological: local, systemic Postsurgical: direct, indirect Degenerative: primary, secondary

follow-up and possible surgical candidates, types II and III indicating mostly conservative treatment, and some slight modifications for type IIIB cases.

Mac-Thiong also proposed a pediatric classification system, based upon dysplastic changes and sagittal spinopelvic balance.²⁴ This description focuses on guidelines for surgical management, considering sagittal balance restoration as one of the main goals for treatment of all types of SL, regardless of etiology. Mac-Thiong divided the disease into three main groups: low grade (Meyerding 0, 1, and 2), high grade (Meyerding 3 and 4), and spondyloptosis. These categories are further divided then separated into low and high-dysplastic subtypes, and further divided based on sagittal spinopelvic balance. Use of the Marchetti classification is recommended for communicating with patients, as it comparatively minimizes medical jargon. The Scoliosis Research Society has adopted the Marchetti classification as the recommended system³⁰; however, the Mac-Thiong classification is recommended for surgical guidelines and the Herman-Pizzutilo classification for conservative management. Each classification system has associated advantages, and until a comprehensive and treatment-based algorithm has been developed, it is recommended that all criteria be taken into consideration during management decision making.

CLINICAL PRESENTATION

Patients with SL may never seek medical attention because the pathology is often asymptomatic. Those who do seek care can present with a variety of symptoms; however, lower back pain is the most common complaint. The treating physician must attempt to elucidate the underlying cause of the pathology.

Medical History

The managing clinician should be aware of the following³¹:

- *Past medical history:* Birth details, neurologic or metabolic disease, hyperlaxity, or any other relevant previous history must be taken.

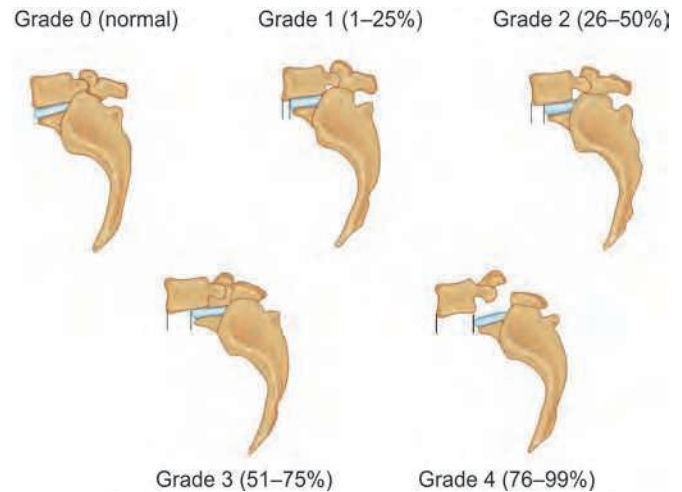


Fig. 108.1: Meyerding grading system for spondylolisthesis.

- Onset and history of pain.
- *Characteristics of pain:* Related to sport activities, worse with sitting or standing, episodic or continuous, intensity of pain, local back tenderness, or associated with irradiating pain to buttock or posterior thigh (note that most young patients do not have classic root tension signs).
- *Duration of pain:* Pain with longer history is more likely related to spondylolysis than new-onset pain.
- *Traumatic factors:* A specific traumatic event or specific sports including gymnastics or swimming. Classical symptoms include the following³²:
- *Mechanical lower back pain:* Pain exacerbated with motion such as sports and similar activities and not painful at rest. This pain occurs due to abnormal load transfer across the vertebral endplates and disc, specifically where the degenerative process begins. Pain may come from the inflammatory process near the lytic site. This may be the reason why facet and lytic site injections can alleviate pain. The intensity and frequency of painful events are highly variable, and depend on many factors. In adults, there is a trend toward increasing pain related to degenerative disc changes; however the evidence for this is conflicting.
- *Leg pain:* Most children will not present with the classical symptoms of radicular as pain described in adult populations. Irritated nerves present as tenderness in the posterior thigh, with associated pain, numbness or tingling. These symptoms, if present, are worsened with exercise and do not subside at rest. It is very unusual to

find motor or sensory deficits, or neurogenic claudication. In children, compensatory mechanisms for this pain include lumbar muscular spasms, diminished leg straightening, and forward bending. In a study of 415 patients, Lafond found that only 25% of children with spondylolysis or SL experienced pain before 20 years of age, and about 9% sought medical attention.³³ Most high-grade SL develops during adolescence, typically when the patient becomes symptomatic.^{5,25,34}

- *Phalen-Dickson sign*: This has been described as an abnormal gait characterized by tight hamstrings, bent knees, and flexed hips. The clinician may also notice exaggerated lumbar lordosis and more prominent buttocks. If associated with herniated nucleus pulposus, make sure to be on the lookout for radicular findings and possible bowel/bladder control findings. Usually present in high-grade SL, pain appears in adolescence and can have a combination of symptoms including the following:
 - Sciatic pain
 - Vertical sacrum and pelvis
 - Lumbosacral kyphosis
 - Tight hamstrings
 - Abnormal pelvic waddling gait.

Physical Examination

The physical examination may range from that of a classic presentation to no significant findings. In spondylolysis and in low-grade SL, there are often no clinical signs to make a diagnosis, and back pain may not appear during the clinical examination. Some may have minimal pain with extension or flexion, although these may be irrelevant or related to other common causes of lower back pain in children. In high-grade disease states, more specific signs appear. Therefore, a typical static posture with a lumbar kyphosis, tight hamstrings, and variable lordosis in the lumbar spine provides the classical presentation of these children.

Depending on the degree of slippage and pain, children and adolescents may present with the following characteristics:

- Hyperlordosis of the lumbar spine
- Sagittal misalignment (lumbosacral “step off” on palpation of spinous processes)
- Deviation of the trunk

- Flexed knees (for compensation of horizontal sacrum)
- Tight hamstrings (reflecting some root irritation)
- Paraspinal muscle spasm (depends on pain present)
- Gait disturbances (high grade and ptosis, also L5 root entrapment)
- Sensorimotor deficits (high grade, nerve root impingement)
- Bowel or bladder dysfunction (extremely rare)
- Associated scoliotic deformity, occurring in some patients.

Pain provocation with different movements (i.e. flexion for discogenic pain or extension with facet joint pain) is not a reliable measure for diagnosis. In the differential diagnosis, specific pathologies commonly diagnosed in childhood should be considered. These may include neurofibromatosis, Marfan’s syndrome, Ehlers-Danlos syndrome, myelomeningocele, and osteogenesis imperfecta.

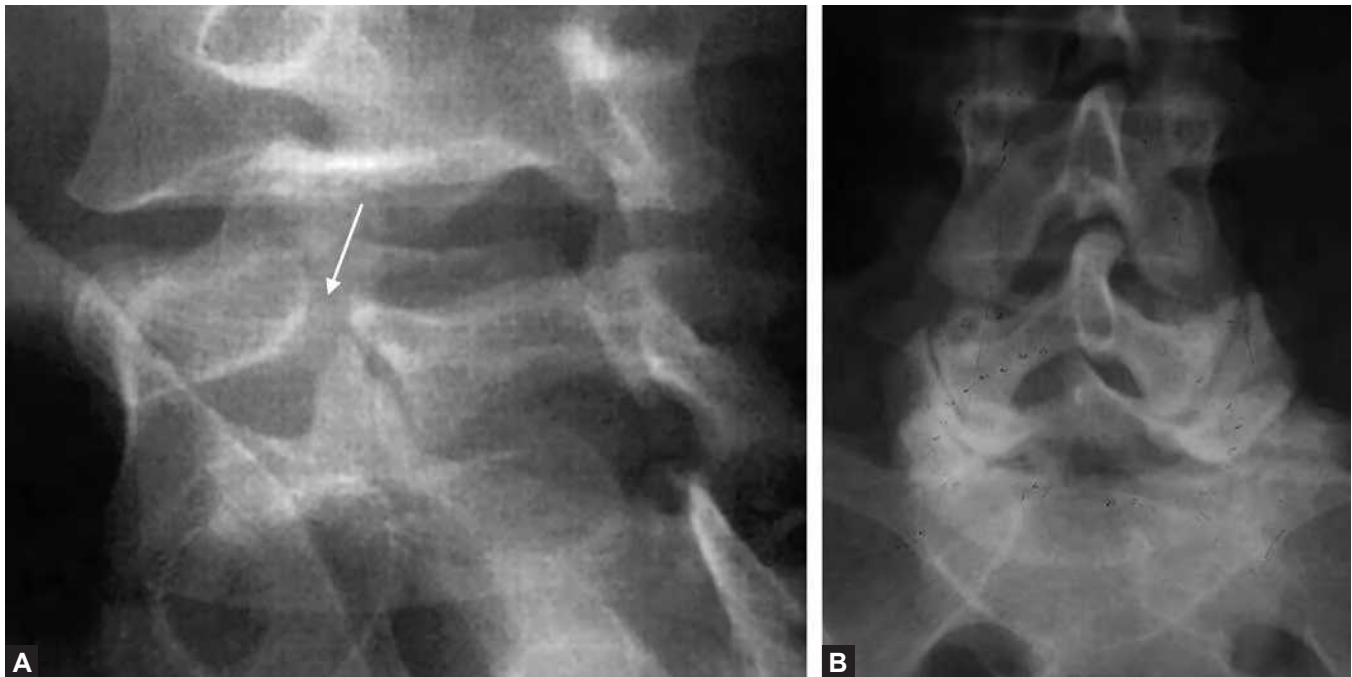
Diagnostic Workup

After clinical evaluation, imaging is essential to fill in gaps from the physical examination. Unfortunately, there is a sparse correlation between pain and radiologic changes. Thorough conservative treatment based upon imaging and physical examination, in conjunction with judicious surgical indications, is essential for adequate treatment.

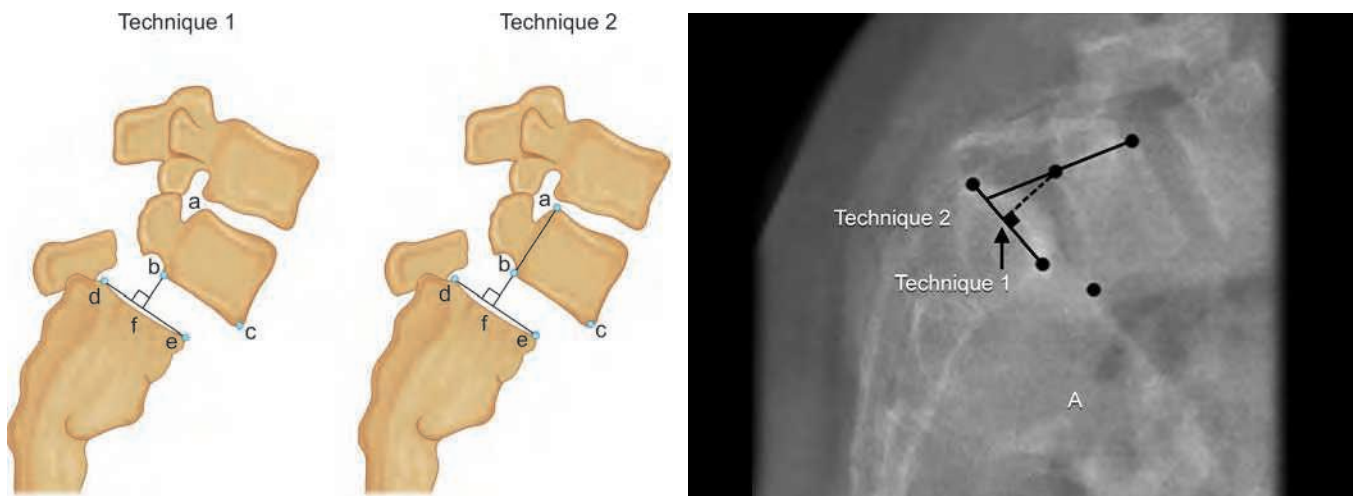
Radiographic Examination

Collimated lateral and true anteroposterior (AP) angled radiographs will provide necessary findings. On lateral films, the displacement, slip angle, sacral dome deformity, and L5 morphology are examined. The pars defect is also sometimes identified; on AP films, it is possible to find a pars defect along with the “Napoleon hat” sign in high-grade slips. On oblique radiographs, the pars defect is observed with a pathognomonic “Scotty Dog Collar” sign. Full-length films including the pelvis are essential to evaluate associated deformities, spinopelvic parameters, and sagittal balance. This important evaluation is necessary for surgical decision making. The chronicity of the pars lesion may be anticipated in the presence of sclerotic margins.

There are several ways to measure the translational displacement and severity of slip in SL, as seen Figures 108.2 and 108.3.³⁵ The importance of this measurement dilemma cannot be overstated, as most surgical decisions are made from this finding; description of severity of slips, prognosis, and decision-making all utilize the Meyerding grading system for assessment.



Figs. 108.2A and B: Anteroposterior film demonstrating the classic signs on X-ray. (A) Oblique view, arrow points to the Scotty Dog Collar. (B) Shows the inverted Napoleon Hat sign.



Figs. 108.3: Two different spondylolisthesis measurement techniques. Technique 1 uses the b–f line perpendicular to the S1 endplate (line e–d), whereas, technique 2 uses a tangent to the L5 posterior wall, line a–b. These lines indicate the position of L5 on S1 in point f.

Other important measures include the following:

- Percent of anterior displacement³⁶
- Slip angle; as described by Boxall et al.³⁷
- Percent of rounding on top of sacrum.

These three measurements are described to be valuable in estimating the risk of slip progression in children.^{9–11}

Bone Scan

While SL is often diagnosed with radiographs, bone scans are particularly useful in the diagnosis of spondylolysis. Bone scanning is a useful tool for two main purposes: demonstrating the presence of a pars hypermetabolic

Table 108.3: Treatment algorithm for suspected spondylolysis based on SPECT bone scan and radiology results.⁴¹

<i>Radiology</i>	<i>SPECT</i>	<i>Interpretation</i>	<i>Action</i>
Negative	Negative	Other cause	Consider MRI, look for other diagnosis
Negative	Positive	Probable active lesion	Begin conservative treatment (rest, bracing). Order CT scan
Positive	Negative	Inactive, old lesion	Consider surgical treatment to prevent progression. Investigate back pain further.
Positive	Positive	Active pars lesion	Begin conservative treatment (brace and rest). CT scan for prognostic factors.

(SPECT: Single photon emission computed tomography; MRI: Magnetic resonance imaging; CT: Computed tomography).

activity (mechanical stress or fatigue fracture) and determining the age of onset of the pars lesion. Single photon emission computed tomography (SPECT) bone scans are particularly helpful as they more precisely determine radioactive accumulation and demonstrate a transverse reconstruction of the vertebra.³⁸ Standard radiographs, including oblique views, may produce false negatives, resulting in a persistent doubt of the diagnosis. The SPECT bone scan is preferred over computed tomography (CT) scans to avoid the large radiation dose. Single photon emission computed tomography also enables the treating physician to determine the following^{39,40}:

- The precise localization of the lesion to focus CT scan (if necessary)
- Age of the pars lesion
 - High signal activity lesions suggest healing potential and treatment is advised.
 - No signal activity suggests lack of healing potential, indicating an alternative management course.

A potential algorithm for managing back pain in children in whom a spondylolysis is suspected based radiologic examinations is discussed in Table 108.3.

CT Scan

The best study for bone is a CT scan. This is an essential imaging study for spondylolysis and SL. Particularly in spondylolysis, the clinician should be aware of the possibility of a false-negative study. This may occur when the gantry is positioned perpendicularly to the pars defect. Gantry angle for these studies must be arranged parallel to the pars interarticularis.⁴² With multislice CT scans, one can reconstruct the spine in any desired plane, allowing the precise anatomy of the pedicles and the shape of the spinal canal to be observed, to best determine the presence and degree of compression.⁴³ Also the profile of the foramen can be revealed, with information including vertebral body displacement, posterior arch dysplasia, L5 trapezoidal shape, and the S1 characteristics.⁴⁴

Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) may not be appropriate for evaluating spondylolysis, although it can aid in the diagnosis of SL. This can display characteristics of the olisthetic segment, the study of nerves structures, disc, cauda equina, endplate abnormalities, and facet joint arthritis. Bone edema in the pars suggests metabolic activity, and may indicate the age of the pars lesion. Magnetic resonance imaging may detect edema that a CT may miss, which can lead to a “prelysis” lesion diagnosis, and subsequent treatment.⁴⁵ In high-grade SL with associated neurologic symptoms, MRI is indicated.^{46,47}

Disc degeneration, modic endplate changes, and disc herniations at the olisthetic level may be indications for MRI use. However, MRI has been associated with a high rate of false-positives and a low positive predictive value for pars defect detection.⁴⁸ The study is more commonly used to rule out other causes of back pain, mainly adjacent level disease, herniated discs, and intraspinal tumors. The specific degree of compression on the exiting nerve root can be well visualized with MRI. Use of gadolinium may be helpful, as special sequences for radiculography may show radicular dysfunction.

CT Myelography

While MRI has largely surpassed myelography in diagnostic preference, indications for myelography include the following:

- Contraindications for MRI, including implanted devices such as a pacemaker
- Functional stenosis, mainly dynamic subarticular or foraminal stenosis, which may only be diagnosed by this method
- Postoperative or iatrogenic SL.

It is important to note that independent myelography is of limited significance, and should be performed in conjunction with a dynamic study and CT Scan (i.e. myelo-CT).

Provocative Discography

The use of discography has been controversial for some time, and is no longer part of the diagnostic armamentarium of tests useful in determining the status of the adjacent level disc. The utility of this diagnostic tool has no proven effect on the outcome of surgery, and there are a variety of different factors that may affect the results. For further information, please refer to the Carragee study on discography.⁴⁹

TREATMENT

Nonsurgical Management

Spondylolysis and Low-grade SL

Nonoperative treatment of spondylolysis or low-grade SL is often grouped together as the disease history and outcomes after management are so similar.^{50,51} In a study by Micheli and Wood, pars stress fractures without cortical disruption were observed in 47% of athletes.⁵² In these patients, CT or bone scans were often positive although radiographs were negative (Table 108.3). These lesions may be unilateral or bilateral, with unilateral fractures having a greater chance of healing. In the Beutler et al. study, all unilateral pars fractures healed.⁸ Bilateral stress fractures may heal, although in Beutler's series, no bilateral lytic defects were found to have adequately healed. Sys et al. reported healing of bilateral fractures in elite athletes if treatment was started early, stressing the importance of timely diagnosis on outcomes.⁵³ It should be noted that with bilateral stress fractures, differences in healing may be determined by the etiology of the defect. Traumatic or sports-related injuries are more prone to heal than other types of lesions, whereas old or chronic lesions (seen as hypoactive on imaging studies) were not found to adequately heal. Despite the sparse results in healing, ~90% of these elite athletes were found to return to their previous level of activities.⁵³ This benign natural history in most patients, and the temporal possibility for healing, creates a challenge in treatment decisions. Operative treatment for all patients is unrealistic as the vast majority of surgeries may be unnecessary. On the other hand, delaying surgical treatment will result in diminished rate of healing in the remaining nonhealing group, due to the progressive defect. There is currently a lack of literature regarding risk factors for continuous clinical symptoms in spondylolytic patients, suggesting the need for additional study.

The Cavalier review suggests that early brace treatment is associated with better outcomes than if initiated after a failed trial treatment with sports restriction and anti-inflammatory drugs plus physiotherapy.^{50,54} Some studies have examined the use of different types of corset, although these are based upon few cases with short follow-up. Turner and Bianco recommended a 6-month period of full day corset,⁵⁵ while Blanda et al. used a full day orthotic for only 2 months, followed by an exercise program, yielding an 82% rate of successful treatment in 28 symptomatic patients.⁵⁶ The treating physician should evaluate the psychological implications of a long-term treatment with corsets. Overall, a 75% positive outcome may be expected for spondylolysis and low-grade SL.⁴² Steiner and Micheli⁷⁸ described use of a modified Boston brace with an extension to the thigh for 6–12 weeks as a valuable treatment option.⁴² The rationale behind the thigh extension is to diminish the flexion/extension movement on the lumbosacral junction and to allow bony bridging across the pars defect.

The rehabilitation process should include the following five steps:

1. *Halt inflammatory process:*
 - a. Brief bed rest for 24–48 hours
 - b. Anti-inflammatory drugs for 5–7 days
 - c. Pars anesthetic/steroid block
2. *Enhancement of muscle strength:*
 - a. Isometric in horizontal plane and neutral spine position
 - i. Avoid extension
 - b. Trunk motor control
 - c. Strengthen antigravitational muscles
3. *Flexibility:*
 - a. Hamstring muscle stretching
 - b. Lumbar fascia stretching
 - c. Protected range of lumbar movements. Avoid lumbar extension
4. *Aerobic training:*
 - a. Cross-training (bicycle, elliptic, and hydro gym)
5. *Return to play:*
 - a. Steps 1–4 accomplished
 - b. Sports-related motor control
 - c. Hamstrings adequately stretched
 - d. Aerobic conditioning related to the specific sport
 - e. Progressive return.

Regardless of the rehabilitation process used, individual variation in training and goals should be provided.

Approximately 85% of patients with low-grade SL are asymptomatic and will not require treatment. Patients may

Table 108.4: Treatment guidelines based on etiology.⁵⁷

Etiology	Age	Low grade (Meyerding I-II)		High grade (Meyerding III-IV)		
		Asymptomatic	Back pain only	Back and neurologic symptoms	Back pain only	Back and neurologic symptoms
Developmental	Children	No treatment	Mostly nonoperative	Surgical	Surgical	Surgical
	Adults	No treatment	Mostly nonoperative	Mostly surgical	Nonoperative or surgical	Surgical
Degenerative	Adults	No treatment	Nonoperative or surgical	Usually surgical	Nonoperative or surgical	Usually surgical
Postsurgical	Children	No treatment	Attempt nonoperative	Surgical	Surgical	Surgical
	Adults	No treatment	Attempt nonoperative	Surgical	Surgical	Surgical
Pathologic	Children	Depending on etiology	Depending on etiology	Depending on etiology		
		Depending on etiology	Depending on etiology	Depending on etiology		
Trauma	Children	Depending on etiology	Surgical	Surgical		
	Adults	Surgical	Surgical	Surgical		

become symptomatic after three or four decades in association with disc degeneration, as stated previously in this chapter.

Indications for conservative treatment in low-grade SL include the following:

- No neurologic deficits
- Tolerable pain threshold
- Short duration of symptoms
- Improvement by exercise program
- Improvement with brace treatment
- Minimal comorbidities present
- Strict long-term follow-up for dysplastic low-grade SL.

It is important to be aware of the risk of progressive slippage in skeletally immature patients with dysplastic low-grade SL who are managed conservatively. These patients should be followed closely until adulthood for the development of neurologic abnormalities.⁵¹

The authors prefer to perform conservative treatment based on Wiltse and Jackson's recommendations:

- For up to 25% subluxation in an asymptomatic child, observe with radiographs, initially every 4–6 months if under age 10, semiannually until age 15, then annually until the end of growth. No limitation of sports activities is recommended.
- A slip of 26–50% in an asymptomatic child, use same strategy as previous, with a warning regarding participation

in contact sports or sports with lumbar hyperextension (e.g. football and gymnastics).

- About <50% listhesis in a symptomatic child, initiate nonoperative treatment with bracing, anti-inflammatory medications, exercise with same recommendations as recommended by Wiltse et al.² If pain persists after 6 months, proceed to fusion.
- A slippage of >50% in a growing child, with or without symptoms should proceed to surgery.

Guidelines are described in the following sections for low- and high-grade SL treatment based on etiology (Table 108.4).

High-grade Slips

Children and adolescents with severe symptomatic SL do not respond favorably to nonoperative management, with the relief of symptoms in <10% of patients.⁵⁴ For this reason, surgical treatment is recommended in these patients. Based on the study by Harris et al., which describes the disease evolution and long-term follow-up for patients with severe SL, there is no evidence in support of prophylactic surgical treatment in asymptomatic patients however.³⁴

Surgical Management

A knowledge of the natural history of SL (i.e. slip advancement, progressive and incapacitating pain, or neurologic

deterioration) allows us to determine indications for surgery. The objectives of surgical treatment include the following:

- Prevention of further slip, achieved via stabilization of the olisthetic segment
- Correct associated deformities (i.e. lumbosacral kyphosis and rebalancing the spine)
- Relieve back or leg pain
- Reverse neurologic deficits.

Wild et al. outlined indications for spondylolysis and SL surgery, separating these into absolute and relative.⁵⁸ Absolute indications are defined as progressive neurological dysfunction, slip progression, or high-grade listhesis in pediatric patients, or significant lumbosacral kyphosis with associated gait abnormality. Relative surgical indications include minor or nonprogressive neurological dysfunction, radicular and claudication symptoms, or low back pain unresponsive to nonsurgical management.⁵⁸

The ideal surgical strategy continues to be controversial. Good clinical results have been described with multiple surgical techniques. These approaches include arthrodesis “in situ” with or without postural reduction, instrumented arthrodesis and reduction, and arthrodesis through combined anterior/posterior approach techniques. Selecting the surgical technique should be based upon careful analysis of the patient’s symptoms, clinical deformity and their neurological status. Considerations must also include the technical feasibility, surgeon’s preference and surgeon experience.

“In Situ” Arthrodesis

L4–S1 “in situ” posterolateral arthrodesis continues to be the preferred method of treatment for children and adolescents with severe SL. This procedure is commonly performed through a longitudinal or transverse central incision, or by the bilateral parasagittal approach described by Wiltse. In Wiltse’s approach, the transverse processes of L4, L5, and the sacral ala are widely exposed. When radicular compression is present, a bilateral L5 laminectomy with debridement of the pars interarticularis (Gill’s laminectomy) becomes necessary. An adequate arthrodesis surface preparation and appropriate corticocancellous bone graft are paramount to achieving a sufficient arthrodesis capable of withstanding the shearing forces at the level of the lumbosacral union.⁵⁹

This technique requires immobilization with a spica cast or a thoracolumbosacral orthosis with extension onto the thigh for a period of 8–12 weeks following surgery. In

the presence of deformity with partial mobility, it is possible to attempt a progressive postural reduction while molding the cast or the orthosis, by increasing the lumbosacral lordosis, thus correcting the shearing angle and improve overall sagittal balance. The use of transpedicular instrumentation allows for a reduction in duration of external immobilization during the postoperative period.

Different reports in the literature have shown that “in situ” arthrodesis can be achieved in 70–100% cases, with good results as to lumbar pain relief and neurological improvement in 75–100% of patients. A recent long-term outcome study concluded that the in situ group performed better in nearly all clinical parameters they assessed, and that fusion in situ be considered the method of choice for severe isthmic SL.⁶⁰

There is a risk for progression of the deformity during the postoperative period, which is usually correlated with insufficient immobilization, pseudoarthrosis or elongation of the fusion tissue mass. Pseudoarthrosis is usually asymptomatic, and in the majority of patients, the progression of the deformity is minimal and does not progress symptomatically. Transpedicular instrumentation reduces both the risk of pseudoarthrosis and the progression of the SL during the postoperative period.

In adolescents with severe lumbar pain and neurological symptoms associated to severe SL, the modified “in situ” arthrodesis described by Smith et al. could be implemented.⁶¹ This technique utilizes a structural fibular graft placed through a bony tunnel at the posterior aspect of vertebral bodies L5–S1, in addition to the posterolateral arthrodesis L4, L5–sacral ala, achieving a circumferential arthrodesis via the posterior approach alone. This technique has yielded promising clinical results with regard to pain relief and neurological improvement.

Arthrodesis with Reduction

Reduction of severe SL in children and adolescents is indicated if the shearing angle is $>45^\circ$, severe sagittal imbalance is present, or for patients at risk for developing pseudoarthrosis. Patients at risk for developing pseudoarthrosis are those who need a wide decompression at L5–S1, patients with severe lumbosacral union dysplasia, L5–S1 segment hypermobility, some anatomical variations (small transverse processes, sacral dysplasia, or spina bifida), and the presence of secondary changes at the lumbosacral union level (trapezoidal L5 or a round dome-shaped sacrum). Patients with these characteristics are candidates for fusion with reduction.⁶²

The main objectives of reduction are the following: reduce pelvic tilt, correct pelvic retroversion, reduce lumbosacral kyphosis, and reduce listhesis. The reduction of severe SL posits several possible advantages over the “in situ” arthrodesis technique alone. Reduction favors neural decompression, improves sagittal balance, and achieves a better aesthetic result. Restoring the lumbosacral alignment decreases the shearing forces at the level of the fusion, thus increasing the rates of fusion. To achieve reduction of a severe SL, the hips must be hyperextended in order to force pelvic anteversion and allow horizontalization of the sacrum.

There are many techniques described for severe SL reduction and fusion. These approaches include the following characteristics:

- Halofemoral traction with preoperative pelvic suspension
- Anteroposterior fusion and immobilization with a spica cast placed in hyperextension
- Posterior decompression and posterolateral arthrodesis followed by halofemoral traction
- Anterior arthrodesis in a second-stage reduction through external fixator and posterolateral instrumented arthrodesis
- Gradual intraoperative reduction with posterolateral instrumented arthrodesis
- Anterior release with partial reduction and anterior intersomatic fusion.

The use of instrumentation allows the patients to achieve faster mobilization and rehabilitation, and prevents the postoperative progression of SL. All strategies have proven to be efficient in reducing lumbosacral kyphosis, reducing sagittal translation, and obtaining a successful fusion. Ultimately, the surgeon must determine the optimal method for each case based on his/her personal preferences and experience after analyzing the potential risks associated with each technique with respect to the patient.

The reduction and instrumented arthrodesis is a much more challenging technical strategy, which requires a longer surgical time and has an associated increase in intraoperative blood loss compared to an “in situ” fusion.⁶³

The most serious complication following reduction of an SL is an iatrogenic neurological lesion. This has a direct relationship with the amount of reduction obtained. Isolated L5 radiculopathy is the most common complica-

tion, and is present in up to 30% of patients that underwent a reduction and fusion. During the reduction maneuver, up to 75% of the traction force over the root of L5 occurs in the second half of the reduction. Given the high neurological risk implied by a total SL reduction, it is recommended to perform a wide decompression, partial reduction, and posterolateral instrumented arthrodesis. This technique has proven to be useful and safe in children and adolescents who are not candidates for “in situ” fusion.⁶²

“In Situ” Arthrodesis versus Reduction

The indication for “in situ” fusion compared to fusion with reduction continues to be controversial. The literature is consistent in showing that the most relevant factor to achieve good clinical results is an adequate and solid fusion.

Several retrospective level III evidence reports showed no significant difference in the clinical results between “in situ” fusion and fusion with reduction.⁶⁴ However, the current recommendation is an “in-situ” fusion in those patients with a balanced pelvis (without pelvic retroversion), and fusion with reduction in patients with unbalanced pelvis (with pelvic retroversion). The classification below, posted by the Spine Deformity Study Group (SDSG), aids in describing the deformity, defining the prognosis, and helps guide the surgical treatment (Fig. 108.4).^{18,24,65,66}

Advantages of Reduction

- Re-establishes the sagittal balance
- Decreases pelvic tilt
- Corrects pelvic retroversion
- Transforms the shearing forces into compression forces
- Favors conditions for a solid fusion (8% nonunion)
- Allows for a neural decompression (corrections up to 50%)
- Lowers the risk of progression
- Allows for monosegmental fixations L5–S1
- Allows circumferential fusions adding anterior support through a posterior approach [PLIF (Posterior Lumbar Interbody Fusion) or TLIF (Transforaminal Lumbar Interbody Fusion)]
- Improves clinical results (90% good or excellent).

Disadvantages of Reduction

- Increases the risk of neurological lesions to 20–30% of cases

Slip grade	Sacro-pelvic balance and morphology	Spinal balance	Type
Low-grade	Nutcracker ($PI < 45^\circ$)	—	Type 1
	Normal pelvic incidence ($PI \geq 45^\circ$ and $< 60^\circ$)	—	Type 2
	High pelvic incidence ($PI \geq 60^\circ$)	—	Type 3
High-grade	Balanced (High SS/low PT)	—	Type 4
	Unbalanced (Low SS/high PT)	Balanced ($C7 \leq \text{hip axis}$)	Type 5
		Unbalanced ($C7 > \text{axis}$)	Type 6

Fig. 108.4: Spinal Deformity Study Group spondylolisthesis classification.⁶⁶
(PT: Pelvic incidence; SS: Sacral slope; PT: Pelvic tilt).

- In general, the neurological lesion is mild and transient, although it can be severe and permanent
- The most frequent lesion is the traction of the L5 root
- There is an increased risk of radicular lesion if the listhesis correction is $g > 50\%$
- It is important to perform a wide laminectomy in order to visualize both L5 roots during the listhesis reduction
- Surgery must always be performed using neurophysiologic monitoring.

Long-term Outcomes Studies

Better outcomes were found at 14-year follow-up after posterolateral fusion compared to direct repair of the pars defect.⁶⁷ Greater restriction of ROM (Range of Motion) in the adjacent disc and more rapid degenerative progression of the olisthetic segmental disc were also found, with a worse middle- and long-term clinical success for pars direct repair compared to posterolateral in situ noninstrumented fusion. This suggests a potential lack of benefit from a direct pars

repair. There are many studies describing different rates of successful repair with the various techniques; however, comparative studies have not been well documented. After a 6-month trial period of failed treatment, the safer and more predictable treatment strategy is to perform a posterolateral fusion. Exceptions to this recommendation include a pars defect cephalic to L5, multiple lesions, or low-grade reducible SL.⁶⁸⁻⁷¹

In a longitudinal study of 227 patients under 20 years of age, diagnosed of isthmic SL, Seitsalo et al. concluded the following¹⁴:

- The natural history of SL is associated with disc degeneration and spontaneous stabilization of the olisthetic segment.
- Fusion operations do not significantly accelerate degeneration of the adjacent segmental disc above the fusion at 14-year follow-up.
- There is no correlation between the number and degree of degenerated discs and subjective lower back pain in patients.

In a study of surgical outcomes in spine surgery stratified by diagnosis, Glassman prospectively studied 327 patients, showing that superior HRQOL (Health-Related Quality of Life) outcomes were seen after SL and scoliosis cases.⁷² Ostermann found that in 187 patients treated by posterolateral fusion, the only predictive factor for further slip was the amount of primary slip, and that one third of the surgically treated patients (average slip of 39%) suffered postoperative slip.⁷³ For comparison, in the conservative (nonsurgical) treatment group, the average slip was 16% and only 5% progressed.⁷³

Results from a study by Seitsalo involving 149 children with low-grade SL treated operatively or conservatively showed that while the operative group had greater preoperative pain and initial progression of the slip, those treated with fusion had better clinical outcome and less pain at follow-up evaluation than the conservative group.⁷⁴ None of the patients treated conservatively underwent surgery on follow-up, and those advised for surgery had the same outcome as the nonoperative control group.⁷⁴ In contrast to adult degenerative SL, nonunions (up to 35%) had comparable outcomes to patients who underwent fusion in a long-term follow-up. However, at short-term, patients with nonunion complained of significantly worse pain. Most nonunions were associated with mild slips. The progression of slipped vertebrae was higher (44%) in patients where the posterior elements have been resected as a decompression procedure, compared to 33%

in conservatively treated patients and 18% in surgically treated patients.⁷⁴

Additional decompression was a risk factor for nonunion. Patient's final surgical outcome did not differ with respect to pain or neurologic symptoms,⁴⁹ thus, no laminectomy has to be considered in surgical planning for low grade SL. Important to note is the lack of applicability to children, who have a greater potential for fusion. Seitsalo et al. showed that degenerative changes in the L4–L5 disc after fusion did not differ from the control group at a follow-up of 13.8 years, and no correlation between clinical symptoms and degree of degeneration was found.¹⁴ Lamberg reported similar results in a cohort of patients with nonunion (19% in this series).⁷⁵ Posterolateral in situ fusions yielded better fusion rates than posterior fusions, and 10% of patients had progression of the slip despite operation; however, clinical results were similar to the rest of the group.⁷⁵ Degenerative changes in the adjacent level were only 12% at 21 years, with no perceived clinical relevance.⁷⁵

After a prospective SRS (Scoliosis Research Society) database collection review including 25,432 pediatric cases, Fu et al. concluded that SL surgery contributed to 2.4% of all pediatric spinal operations. Of the 605 cases, 518 involved an instrumented fusion. They found no differences in surgical complication rates or neurologic deficits with instrumented and noninstrumented fusions, with a total complication rate of 10.4%. Complications were highly associated with reduction techniques, with a statistically significant difference.⁷⁶

Although instrumented fusion has shown better fusion rates, it is unclear if this holds true for children undergoing treatment for SL. Most surgeons prefer this method; there is no statistically significant difference in complication rate compared with in situ fusion, and there is relatively simplified postoperative management. Brace use is not indicated, whereas it is for 3 months in noninstrumented fusion.

Spondyloptosis Treatment

Spondyloptosis surgical treatment is one of the most challenging spine surgeries. Patients will present with severe lumbar pain, gait difficulties, and neurological symptoms. The circumferential “in situ” arthrodesis described by Smith and Bohlman is one alternative with relatively low risk for iatrogenic neurological lesion.⁶¹ The Gaines proce-

dures are often used, which consists of a partial vertebrectomy through an anterior approach of L5, followed by a vertebrectomy through a posterior approach of L5 (including a laminectomy and resection of pedicles), adding an instrumented reduction from L4–Sacrum. This is a very demanding technique that allows for realignment of the lumbosacral union and is associated with neurological lesions in up to 30% of the patients. A modified Gaines procedure was recently described, involving excision of the inferior half of the L5 vertebral body anteriorly, and posterior reduction and fusion.⁷⁷

SUMMARY

“In situ” fusion continues to be a very good option for the treatment of severe SL in children and adolescents.

The classification proposed by the SDSG, which differentiates severe SL into groups based upon pelvic balance, allows better description of the deformity, definition of the prognosis, and guidance for the treatment. In accordance with the latter, current evidence suggests that re-establishing the spinopelvic balance is critical to obtain a solid arthrodesis and good clinical results. The current recommendation for patients with balanced pelvis is the “in situ” fusion, and for patients with unbalanced pelvis, the partial reduction. The literature agrees that partial reduction is sufficient, and total reduction is often not necessary. The partial reduction allows for correction of pelvic tilt, lumbosacral kyphosis, restoration of spine–pelvis balance, by correcting the pelvic retroversion.

A solid fusion of the segment is key to achieving good clinical results. The partial reduction increases the rates of fusion as well as the clinical results in patients with unbalanced pelvis.

Prospective studies with better evidence level are warranted in order to accurately determine the role that the reduction plays on clinical results (Table 108.5).

CASE EXAMPLES

Case 1

The subject is a 15-year-old girl with 1 year history of lower back and buttock irradiating pain, tight hamstrings, and abnormal posture (A and B). Radiographs revealed unsuspected low-grade SL, with a high sacral slope of 60°, high pelvic incidence, low pelvic tilt, and high lumbar lordosis of 65°, classified as shear-type low-grade SL with dysplastic

Table 108.5: Mac-Thiong classification based on grade, dysplasia and spinopelvic balance.²⁴

<i>Grade of slip^a</i>	<i>Degree of dysplasia^b</i>	<i>Sagittal spinopelvic balance^b</i>	<i>Suggested treatment</i>
Low-grade (0, 1, or 2)	Low-dysplastic	Low PI/low SS (nutcracker type)	Parts repair (grade 0 or 1) versus in situ L5–S1 PLF ± instrumentation ± reduction ^c for grade 2
		High PI/high SS (shear type)	In situ L5–S1 PLF ± instrumentation ± reduction ^c for grade 2
	High-dysplastic	Low PI/low SS (nutcracker type)	In situ L5–S1 PLF and instrumentation ± reduction ^c for grade 2
		High PI/high SS (shear type)	In situ L5–S1 PLF and instrumentation ± L4 and pelvic fixation ± reduction ^c for grade 2
High-grade (3 or 4)	Low-dysplastic	High SS/low PT (balanced pelvis)	In situ L4–S1 PLF and instrumentation ± pelvic fixation ± partial reduction ^c
		Low SS/high PT (retroverted pelvis)	Partial reduction and L4–S1-pelvic instrumentation and PLF ± L5–S1 IF
	High-dysplastic	High SS/lot PT (balanced pelvis)	Partial reduction and L4–S1-pelvic instrumentation and PLF ± L5–S1 IF
		Low SS/high PT (retroverted pelvis)	Partial reduction and L4–S1-pelvic instrumentation and PLF and L5–S1 IF
Spondyloptosis	High-dysplastic		Circumferential fusion, instrumentation, with or without reduction

(PLF: Posterolateral fusion; IF: Interbody fusion using ALIF, TLIF, or PLIF technique; PL: Pelvic incidence; SS: Sacral slope; PT: Pelvic tilt).

^aAccording to the Meyerding classification.

^bDegree of dysplasia and spinopelvic balance as described in the “Pathogenesis” section of this chapter.

^cCorrection of lumbosacral kyphosis should be given strong consideration when slip angle is >10° and lumbosacral angle is >100°, or Spine Deformity Study Group lumbosacral angle is ≥15°.

posterior elements (C and D). Pain and progression are factors for consideration, and were indications for surgery. An in situ instrumented fusion was performed. The patient's pain resolved completely along with neurologic irritative signs, with complete return to functional activities. Postoperative radiographs and clinical appearance are shown (E to G).

Case 2

The subject is a 25-year-old woman with significant L5 radiculopathy and dysplastic pars. A posterior approach is used and the disc space is released through a TLIF-type approach. The deformity is then reduced and locked in place. The patient is flipped 180° in the same surgical session and an ALIF (Anterior Lumbar Interbody Fusion) is performed in addition to an S1 osteotomy.

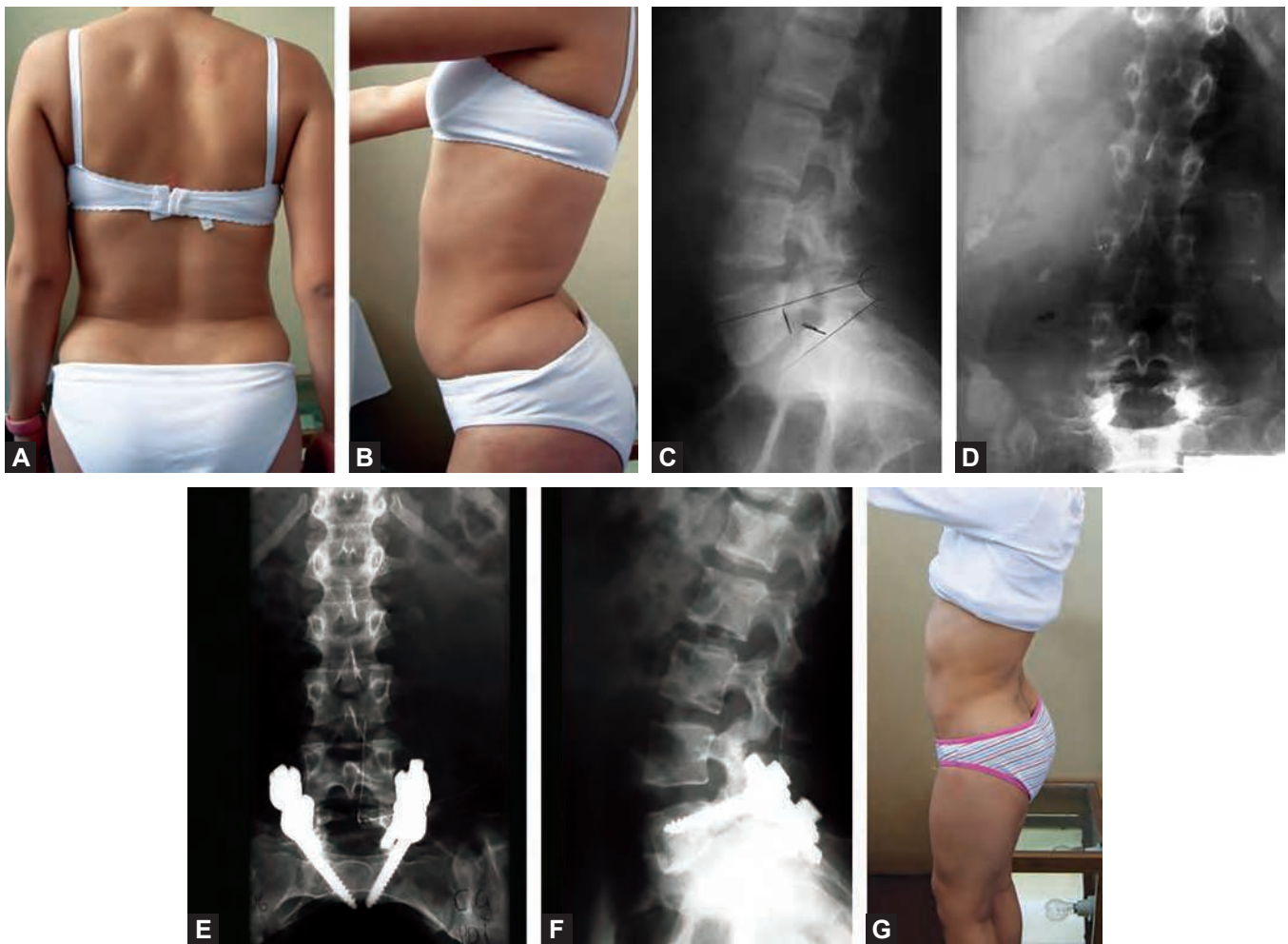
Case 3

The patient is a 32-year-old male farmer with bilateral leg pain and back pain. A posterior approach is performed

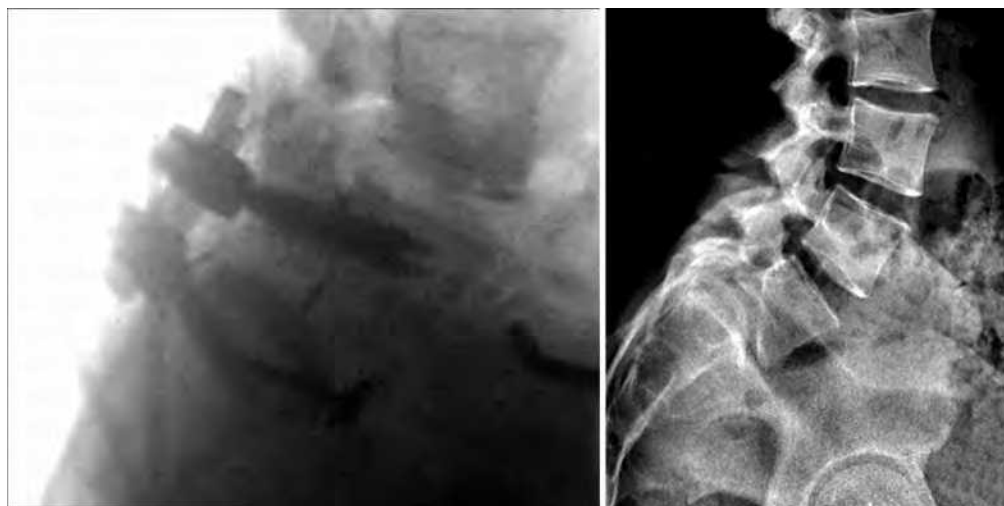
with a Gill laminectomy as well as a TLIF at L5–S1. The L5 and S1 nerve roots are identified bilaterally; the listhesis is reduced; and a posterior spinal fusion is performed with local autograft.

Case 4

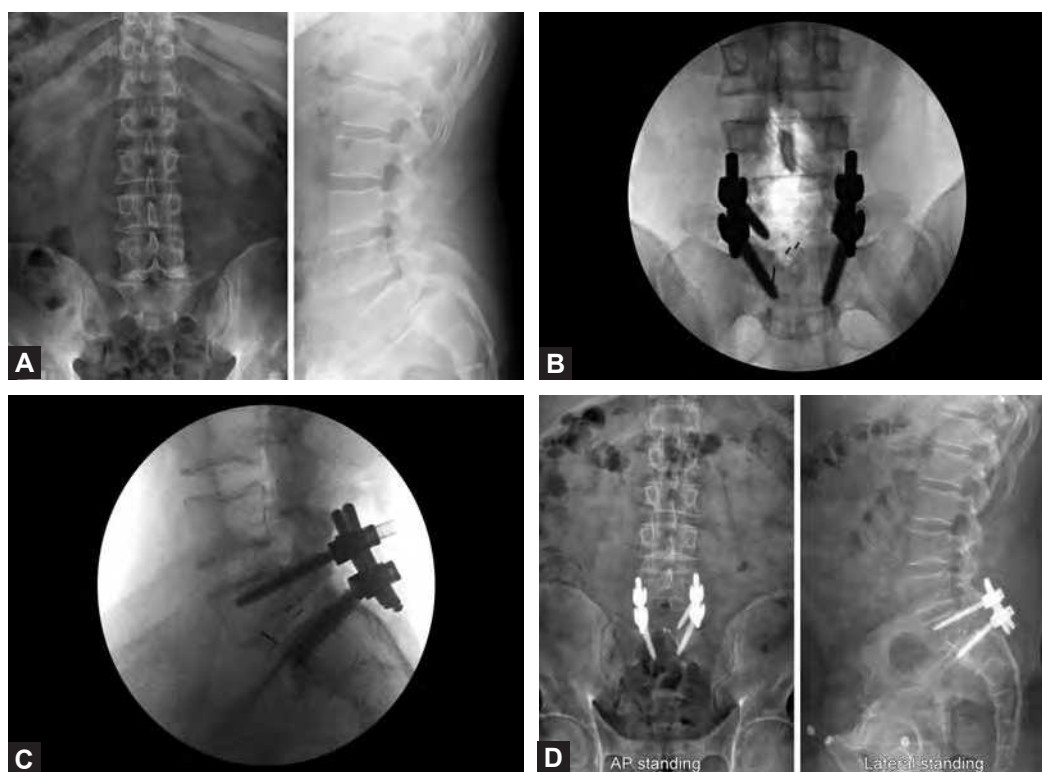
The subject is a 26-year-old female teacher with bilateral leg pain and hamstring tightness. A posterior approach is performed with a Gill laminectomy at L5. The bilateral L5 and S1 nerves identified and visualized and a TLIF is performed at L4–L5 and L5–S1. L5 is reduced onto S1 and a posterior spinal fusion is performed with local autograft. Fusion and stabilization to L4 is then performed in order to achieve solid fixation of proximal segments in high-grade slip. Interbody grafts are placed at L4–L5 and L5–S1 to restore anterior column support, help restore lumbar lordosis, and increase fusion surface area.



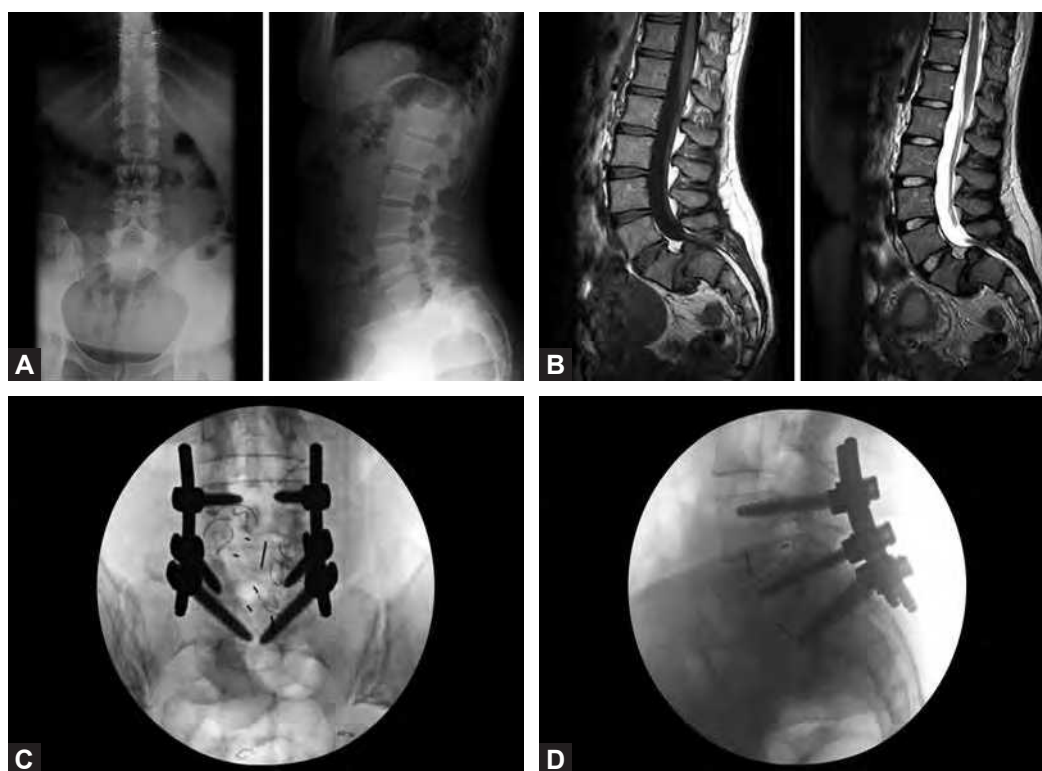
Case 1: A and B are clinical posterior and lateral views. C and D lateral and AP X-rays. E and F postoperative films in AP and lateral views, showing in situ posterolateral fusion with resection of posterior L5 arch. G shows clinical sagittal aspect, with normalization of lordosis.



Case 2: Postoperative lateral views.



Case 3: (A) Preoperative AP and lateral radiographic views. (B to D) Postoperative AP and lateral radiographic views.



Case 4: (A) AP and lateral radiography. (B) Lateral MRI views. (C and D) Postoperative AP and lateral radiographic views.

KEY POINTS IN EPIDEMIOLOGY

- The incidence of spondylolysis is 2–6% in the pediatric population.
- There are many racial or genetically related differences in the prevalence of SL.
- Most cases of SL will not progress after 20 years of age.
- The majority of patients with low-grade SL will remain asymptomatic or with minimal symptoms, and enjoy a quality of life similar to that of the normal population.
- About 90% of slips occur before the first clinical evaluation.
- Despite disease progression (referring to disc degeneration in the olisthetic segment), there is no correlation with increased occurrence of low back pain.

KEY POINTS IN PATHOGENESIS

In summary, the etiology of SL is related to each of the following, and characterized by the unique anatomical and functional characteristics of the lumbosacral segment:

- Hereditary
- Spinal balance
- Physical activities
- Dysplastic segment
- Slip angle or lumbosacral angles.

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Immature Spine and Athletic Injuries

Toshinori Sakai, Koichi Sairyo

Snapshot

» Cervical Spine Injuries in Pediatric and Adolescent Athletes

» Thoracic/Lumbar Spine Injuries in Pediatric and Adolescent Athletes

INTRODUCTION

Understanding specific features of the immature spine enables a better understanding of pediatric spinal injuries. Vertical growth of the vertebral body occurs mostly at the chondroepiphyseal portions of the endplates. These areas enable circumferential expansion, while the posterior elements demonstrate longitudinal growth. An anterior growth plate exists at each neurocentral synchondrosis, and a posterior growth plate at the spinous process synchondrosis enables lengthening of the laminar and pedicular regions. Posterior element growth ceases at 5–8 years of age, after synchondroses closure, and anterior column growth continues until 17–18 years of age.

The term “ring apophysis” applies to the thickened periphery of the endplates and is the result of the ellipsoid enlargement of both the intervertebral disc and the primary ossification center. The central epiphysis thins, while the circumferential portions remain thick.¹

Skeletal maturity can be evaluated on lateral view plain radiographs by assessing the appearance of the secondary ossification center of the L3 vertebra (Fig. 109.1). The maturity stage of the vertebral body is classified as (1) the cartilaginous (“C”) stage, indicating that the secondary ossification center of the vertebral body is not visible on the radiograph; (2) the apophyseal (“A”) stage, indicating that the secondary ossification center of the vertebral body is visible on the radiograph and an ossified fragment is confirmed at the edge of the vertebral body; or (3) the

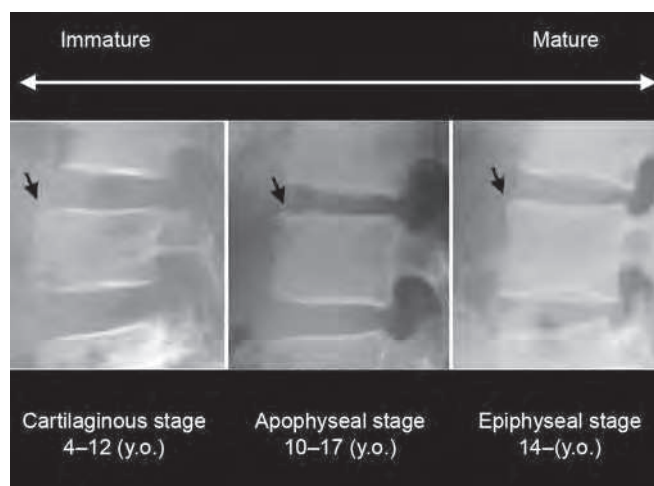


Fig. 109.1: Maturity stage of the vertebral body. Cartilaginous stage—no secondary ossification center of the vertebral body is visible (arrow). Apophyseal stage—the secondary ossification center of the vertebral body is visible (arrow), and an ossified fragment is evident at the edge of the vertebral body. Epiphyseal stage—the apophyseal ring is fused to the vertebral body (arrow). (y.o.: Years-old).

epiphyseal (“E”) stage, meaning that the apophyseal ring is fused to the vertebral body, suggesting vertebral maturation. Note however that the words “apophysis” and “epiphysis” are acknowledged as misnomers.^{2–4} Vertebral apophyseal ring fracture is a disease specific to the C- or A-stage immature spine. Furthermore, regarding isthmic spondylolisthesis that occurs subsequent to spondylolysis, slippage is more prevalent in individuals with a younger

skeletal age whose lumbar spine is immature, and it halted during the epiphyseal stage after the growth period when the vertebra had matured.²

CERVICAL SPINE INJURIES IN PEDIATRIC AND ADOLESCENT ATHLETES

Fractures of the Cervical Spine

Cervical spine injuries are potentially devastating and result in significant morbidity and mortality. The major mechanism of serious cervical injury is axial load—a large compressive force applied to the top of the head. This mechanism is more dangerous when the neck is in a slightly flexed position. The bimodal age distribution of patients sustaining cervical spine injuries shows a large peak at around 13–15 years and a smaller peak at around age of 5 years.^{5,6} Younger children are more likely to sustain cervical spine injuries caused by motor vehicle-related incidents, whereas older children and adolescents are more likely to incur cervical spine injuries during sports activities. The incidence of cervical spine injuries resulting from sports-related activities may be reduced by paying attention to physical conditioning and strengthening and managing regulations.

Burners and Stingers

Burners or stingers commonly occur in athletes participating in contact sports such as football, ice hockey, diving, and wrestling. The incidence of this transitory brachial plexus injury is approximately 30–50% over the course of a high school, college, or professional football player's career. Symptoms are severe burning or searing pain in the upper extremity after injury, and most injuries occur by one of three mechanisms: traction, compression, or hyperextension and compression. These injuries are clinically classified as neurapraxia, neurapraxia/axonotmesis, and neurotmesis according to their symptoms and the pattern of symptom resolution.

Most athletes can recover completely and return to sports activity following conservative treatment. Protective equipment and athlete education are required to decrease the occurrence of these injuries.

Cervical Spondylolysis

Cervical spondylolysis is rare; only 104 cases have been reported in the literature.⁷ Although no cases of cervical

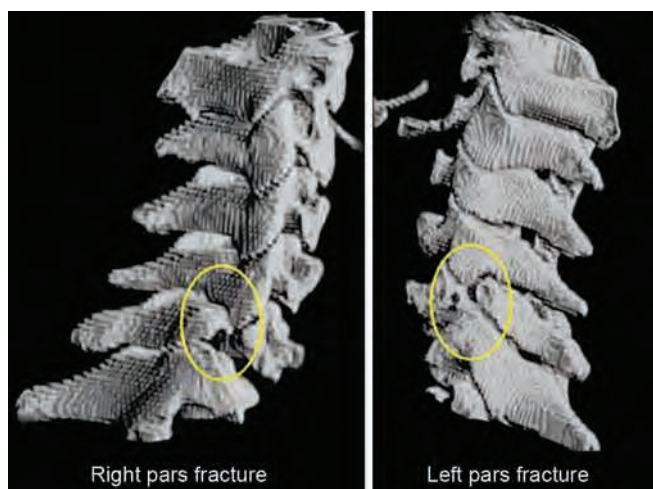


Fig. 109.2: Three-dimensional reconstructed computed tomography scans of the cervical spine. Yellow circles indicate the bilateral location of cervical spondylolysis at C6.⁸

spondylolysis have been found in active athletes, no treatment strategies for athletes with cervical spondylolysis have been established. However, both cervical and lumbar spondylolysis could occur in athletes. Biomechanical results have shown that the increased disc stress and induced hypermobility in cervical kinematics observed in cervical spondylolysis may lead to cervical spinal cord injury when compared with an intact cervical spine (Fig. 109.2).⁸ Therefore, patients with cervical spondylolysis should abstain from any kind of contact sport.

THORACIC/LUMBAR SPINE INJURIES IN PEDIATRIC AND ADOLESCENT ATHLETES

Fractures of the Thoracic/Lumbar Spine

Pediatric spinal injuries constitute 1–10% of all spinal injuries, and the incidence of thoracic/lumbar injuries in children and adolescents varies between 5.4% and 34%.^{9–11} From a review of 89 pediatric patients with thoracic, lumbar, or sacral injuries by Dogan et al., the thoracic region was most affected (46%), followed by the lumbar (29.8%), thoracolumbar (19.2%), and sacral regions (5%).¹² Multi-level injuries are common and warrant imaging evaluation of the entire spinal column. In their review, the incidence of fracture caused by sports-related accidents was 21.3%, with 74% of all patients treated conservatively.

Many authors have advocated nonsurgical management consisting of bed rest or immobilization with a cast

or thoracolumbosacral orthosis for stable fractures in the pediatric population.^{13,14} The need for surgery depends on the type, level, and severity of the injury. Factors include persistent instability and significant compression fracture of the vertebral body (40% or more spinal canal compromise and/or 40% or more loss of spinal canal height), spinal kyphotic deformity of $>20^\circ$, vertebral dislocation, and spinal cord compression associated with progressive neurological symptoms.^{15,16}

Lumbar Disc Herniation

Lumbar disc herniation (LDH) is a common disorder in adults, but has a low prevalence in children and adolescents. In fact, pediatric patients constitute only 0.5–6.8% of all patients hospitalized for LDH.^{17–19} In a cohort study of 12,000 persons by Zitting et al., LDH leading to hospitalization first appeared around the age of 15 years, and the cumulative incidence increased sharply from the age of 20 in men, while increasing steadily in women.²⁰ By the age of 28 years, 9.5% of males and 4.2% of females were hospitalized for LDH, respectively.

There are several potential causes for pediatric LDH. A history of trauma before the onset of symptoms is a controversial predisposing factor. A review of the literature revealed that trauma including sports-related or self-reported injury is commonly considered the most likely cause of LDH because 30–60% of symptomatic pediatric patients have a traumatic history.^{21–26} A retrospective analysis of 165 patients identified a triggering event in 40% of LDH cases,²⁷ while another report showed that 82% of adolescent patients sustained trauma or were involved in intense sports activity.²⁸ On the contrary, the results of a retrospective analysis performed by Kumar et al. on 25 patients showed that only two patients (8%) had a history of significant trauma.²⁹ Regarding the association with athletic activities, magnetic resonance imaging (MRI) of asymptomatic adolescent elite tennis players showed that disc degeneration including LDH was present in 39.4% of all subjects.³⁰ Among elite swimmers, 68% had degenerative discs at various disc levels.³¹

Genetic factors are also considered predisposing factors. A family history of LDH was 67.8% in a retrospective analysis of 165 patients,²⁷ and Matsui et al. reported a familial predisposition for lumbar degenerative disc disease in their case-control study.³²

Diagnostic Imaging

Although the relationships between anatomic abnormalities of the lumbar spine detected by MRI, clinical history,

and patient outcome are controversial, MRI is an effective way of imaging LDH and neural structures. In addition, its noninvasive nature is suitable for pediatric patients.

Conservative Treatment

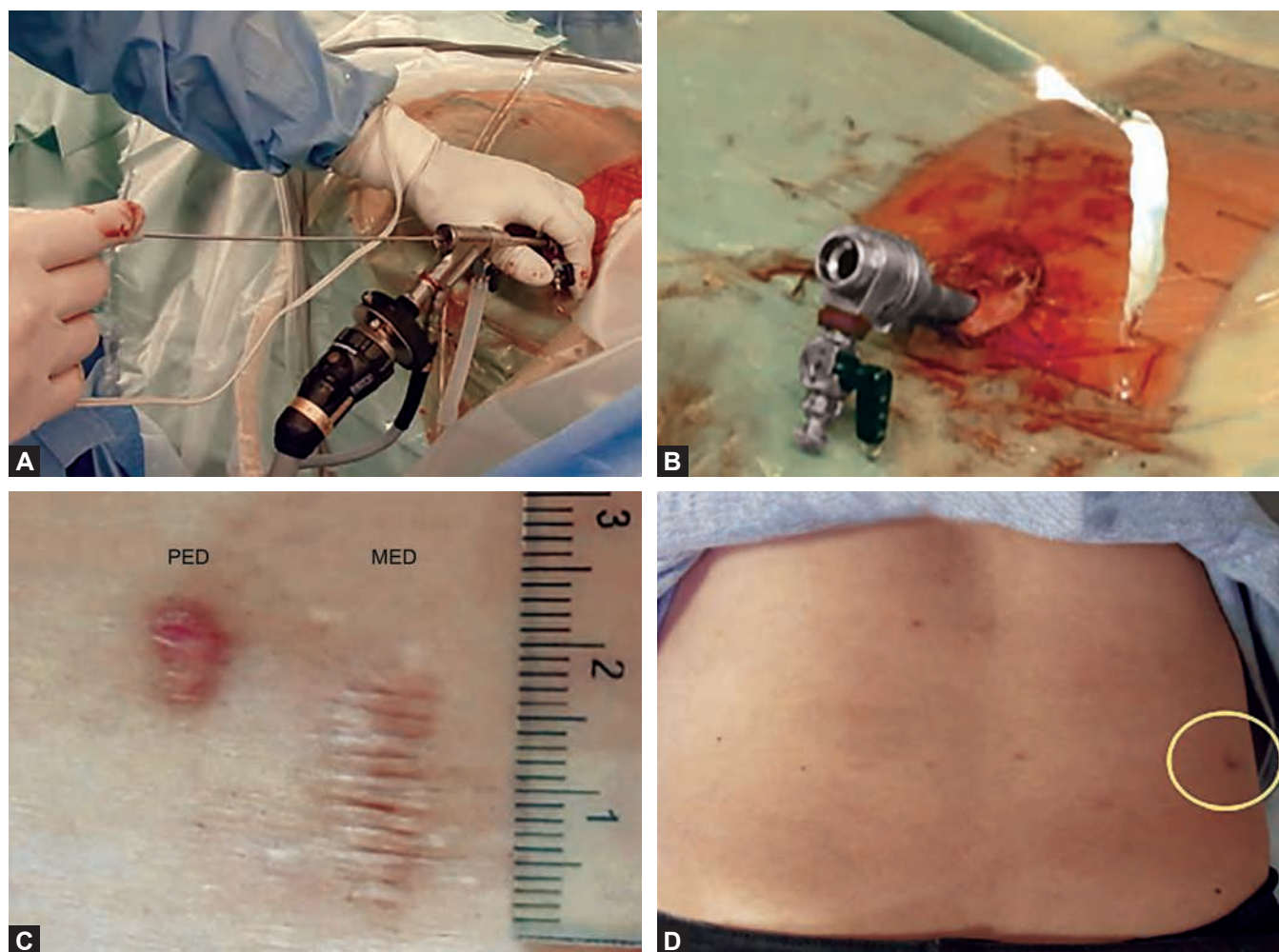
Conservative treatment for pediatric LDH patients consists of activities as tolerated, analgesic and nonsteroidal anti-inflammatory drugs, physical therapy, and limitation of athletic activities, which is similar to the treatment for adult LDH patients. A recent review of current treatments for LDH in children and adolescents by Dang et al. revealed that conservative treatment is not as effective in pediatric LDH patients as it is in adults.³³ They also provided several explanations for the disappointing results of conservative treatment in pediatric LDH patients. (1) Compared with adults, herniated nucleus pulposus in children has lower degeneration and is more hydrated, softer, and viscous,^{24,29,34} which means it might not dry up and be resorbed like a degenerated adult disc.³⁵ (2) Pediatric LDH is often associated with trauma where the annulus fibrosus could be severely ruptured.³⁶ (3) The apophyseal ring of the vertebral body in children and adolescents is not fully fused, hence severe trauma could rupture the apophyseal ring, forming a large implastic mass along with the herniated disc.³⁷ (4) Children and adolescents are active and less likely to comply to strict bed rest.

Surgical Treatment

Indications for surgical treatment include persistent symptoms despite conservative treatment, cauda equina syndrome, progressive neurological deficits, and associating spinal deformities.^{21,35,38,39} Several surgical procedures are available and include percutaneous endoscopic discectomy (PED), microendoscopic discectomy (MED), microsurgical discectomy or microdiscectomy (MD), open discectomy (OD) with/without laminotomy or laminectomy, and spinal fusion. To simplify the understanding of treatment options, these procedures are divided into two groups: “PED”, which includes PED and MED, and “OD” which includes the other procedures.

Percutaneous Endoscopic Discectomy

With the increasing use of endoscopic surgical techniques in spinal surgery, Mayer et al. applied endoscopy to the treatment of pediatric LDH.⁴⁰ Although they used the term “PED” in their case series, their procedure differed from



Figs. 109.3A to D: Herniated nucleus pulposus treatment. (A and B) Endoscopic control of nucleus pulposus removal. (C) Difference in wounds between percutaneous endoscopic discectomy (PED) and microendoscopic discectomy (MED). The patient underwent revision surgery with PED. (D) The circle shows the wound following PED.

conventional PED and is better considered as MED. In 1997, Foley and Smith described MED as a new percutaneous technique and in 2002 reported their first established results.⁴¹ Microendoscopic discectomy has since been adapted to the treatment of several diseases such as LDH, apophyseal ring fracture, and lumbar spinal canal stenosis. However, in 2010, Teli et al. reported a higher occurrence of severe complications (dural and root injuries, and recurrences) and surgical costs with MED compared with MD and OD.⁴²

Recently, PED was introduced as the least invasive procedure for LDH (Figs. 109.3A to D). Details of its surgical technique, outcome, and complications in 307 consecutive cases were first reported by Yeung et al. in 2002.⁴³ With PED, an 8-mm incision is sufficient for

inserting the percutaneous endoscope into the disc space for removal of herniated nucleus pulposus under local anesthesia. Although no long-term follow-up has been reported, several case series and case studies have been published.⁴⁴⁻⁴⁶ In the near future, PED is likely to be indicated for many pediatric LDH patients due to the procedure's low invasiveness.

Open Discectomy

Microdiscectomy consists of a 2- to 3-cm lumbar incision and minimal bone removal and is performed extensively in adults with low complication rates.⁴⁷ Cahill et al. reported the surgical results of a large single-institution series of MD in a pediatric population.⁴⁸ Their results showed that

MD is a safe option for pediatric patients. Postoperative infection, postoperative cerebral spinal fluid leak, and new postoperative neurological deficits each occurred in 1% of cases, with only 6% of patients needing revision surgery, and one patient requiring lumbar fusion.

Compared with PED, OD is associated with more sufficient decompression, but extensive dissection of soft tissues can also result in postoperative back pain. Since children and adolescents have greater nerve root tension than adults, extensive manipulation during discectomy should be avoided to avert nerve damage.⁴⁹ This limitation can be overcome by using MD; the small incision and the use of a microscope can reduce the risk of excessive nerve root manipulation and the likelihood of overlooking sequestered disc material.

Apophyseal Ring Fracture (Posterior Apophyseal Endplate Lesions)

A lesion of the lumbar posterior vertebral endplate, termed an apophyseal ring fracture, in children and adolescents causes symptoms similar to those of a herniated lumbar intervertebral disc. The end-plate lesion has been described as an apophysis, an ossified vertebral rim, an avulsion of the rim, or a fracture of the vertebral body.⁵⁰⁻⁵⁵ Apophyseal ring fractures likely result from mechanical stress applied to the apophyseal ring, which can lead to fracture of the vertebral growth plate.^{2,56,57} This fracture is more common in children and adolescents participating in sports.

Diagnostic Imaging

Diagnosis of posterior apophyseal ring fracture is made on plain radiography or computed tomography (CT) (Fig. 109.4). Although plain radiography showed an avulsed fragment in approximately 40% of cases,^{58,59} CT delineated the size, shape, and site of the fracture fragment clearly. In particular, multi-detector three-dimensional CT is useful for detecting such fragments; MRI had diagnostic utility in only 22% of cases.⁵⁹ Careful review of plain radiographs, supplemented by targeted CT, is necessary for the correct diagnosis and management of this entity.

Treatment

The principle of conservative treatment is similar to treatment for LDH and consists of bed rest, administration of analgesic and nonsteroidal anti-inflammatory drugs

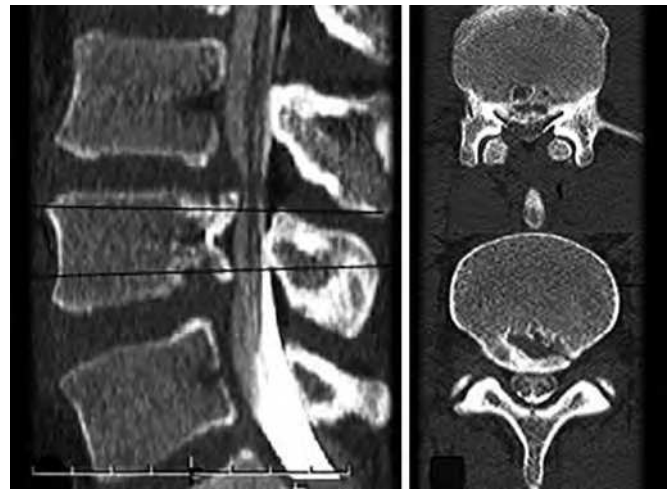


Fig. 109.4: Reconstructed computed tomography scans showing the osseous fragments of the cross-sectional area at both the inferior and the superior L4 rim.

(NSAIDs), physical therapy, and limited physical activity with a lumbar or lumbosacral trunk brace.⁶⁰ Recently, Higashino et al. reported the long-term outcomes of conservative and surgical treatments in children and adolescents.⁶¹ Regardless of treatment, long-term outcomes were favorable. However, to facilitate rapid recovery and return to daily or physical activities, many authors have emphasized the need for operative treatment when conservative treatment fails. The purpose of surgical treatment is not only to decompress the neural structure but also to minimize surgical invasion and avoid related complications. Surgical treatment modalities involve removal of disc and bony fragments with or without spinal fusion.

Lumbar Spondylolysis

Lumbar spondylolysis is a defect of the pars interarticularis known to occur as a stress fracture in childhood or adolescence (Fig. 109.5). Since Wiltse et al. suggested in 1975 that spondylolysis begins as a fatigue fracture of the pars interarticularis,⁶² many studies describing the association of sports activities with spondylolysis have been published. The prevalence of lumbar spondylolysis is notably higher in athletes compared with the general population (6%);⁶³ the incidence of spondylolysis was reported to be 11% in female gymnasts⁶⁴ and 20.7% in college football players.⁶⁵ Among young athletes with low back pain, 47% had lumbar spondylolysis.⁶⁶

Biomechanically, high stress at the pars interarticularis is found in lumbar movements of extension and rotation,



Fig. 109.5: Lumbar spondylolysis. Typical oblique view of plain radiograph showing the Scottish dog's collar sign (arrow).

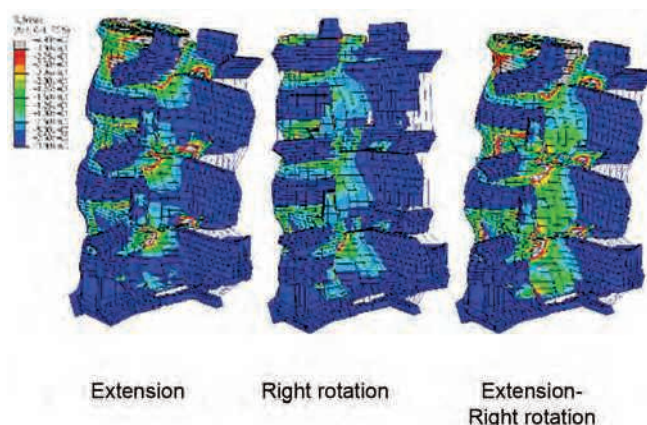


Fig. 109.6: von Mises stress distribution for different lumbar motions. Three lumbar motions showing the highest stresses during combined lumbar extension and right rotation compared with the simple extension/right rotation.

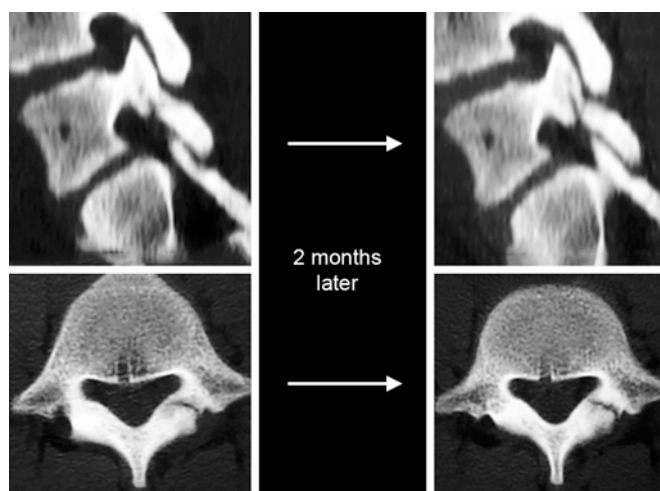


Fig. 109.7: Computed tomography scans of 12-year-old girl who did not comply with conservative treatment. The fracture line at the caudal-ventral aspect of the pars extending to the cranial-dorsal side 2 months after diagnosis.

which are considered the most likely motions to induce a stress fracture at the pars interarticularis (Fig. 109.6).⁶⁷ Furthermore, stress increases when the motion includes both extension and rotation. Two theories pertain to the initial event as a stress fracture. First, on the lumbar spine during extension, the inferior articular process of the cranial vertebra impacts the pars interarticularis of the caudal vertebra.^{62,68} Repetitive impacts of this nature can produce a stress or fatigue fracture of the pars interarticularis, which can be explained as direct compression by means of a “nutcracker” mechanism. Second, the pars interarticularis

breaks under tension through a traction mechanism.^{69,70} Observation of clinical cases and the results of a biomechanical study revealed that spondylolysis as a stress fracture is initiated from the ventral aspect due to the higher concentration of stress at the site during lumbar motion (Fig. 109.7).⁷¹ Thus, there is no doubt that spondylolysis is a stress fracture. However, many aspects regarding the etiology of spondylolysis remain to be clarified.

Clinical Presentation

When adolescent athletes have low back pain that is aggravated by athletic movement, lumbar spondylolysis should be considered. In particular, if low back pain is induced by lumbar extension and/or rotation, Kemp's test will be positive and pinpoint tenderness will be observed on the spinous process of the affected vertebra, making lumbar spondylolysis the most likely culprit. Sometimes, low back pain is accompanied by radiculopathy, which is thought to be induced by extraosseous hematoma or edema at the site of spondylolysis.⁷²

Diagnostic Imaging

It has been noted that bony union of the pars defect can be achieved in children if they refrain their sports activities and wear a trunk brace. To attain bony union, early diagnosis is extremely important to promote bony healing of the pars, and the stage of the defects at the first presentation largely affects prognosis following conservative treatment (Fig. 109.8).⁷³ Furthermore, high-signal change in the

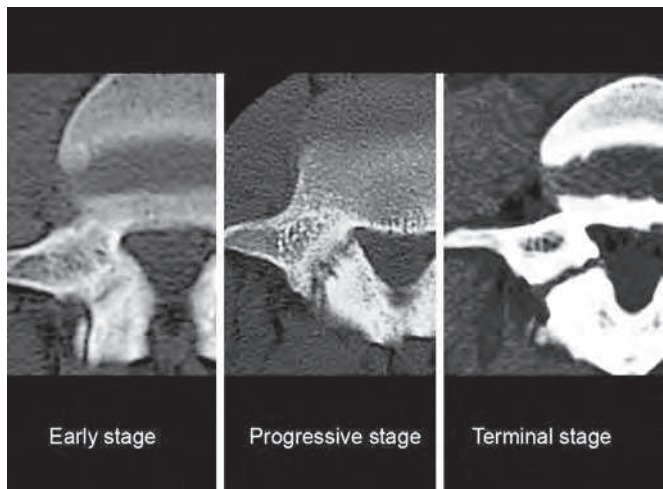


Fig. 109.8: Representative computed tomography (CT) scans of pars defects in each stage. On the basis of CT findings, the defect is classified into three stages: early, progressive, and terminal.⁷³

pedicle adjacent to the pars defect on T2/short TI inversion recovery—MRI has been shown to be an indicator of early-stage spondylolysis (Fig. 109.9).^{74,75} Therefore, axial slices through the pedicle combined with standard images around the disc space should be obtained by screening MRI to avoid missing early-stage spondylolysis in children and adolescents.

Conservative Treatment

In pediatric patients with lumbar spondylolysis, the ideal goal is to achieve bony healing conservatively. For patients with early-stage or progressive-stage spondylolysis, the ideal goal is to attain bony union. As lumbar extension and rotation are risk factors, restricting trunk extension and rotation is considered an optimal approach for achieving bony union. Therefore, conservative treatment involves wearing a molded plastic hard thoracolumbosacral orthosis and refraining from all athletic activities.^{76,77} In most cases, 3–6 months are required for bony healing (Table 109.1). However, for patients with terminal-stage spondylolysis, achieving bony union with conservative treatment is impossible, as conservative treatment consists of pain management to support a return to athletic activities. Sometimes, inflammation is present at the pars defects and adjacent facet joints, which may cause low back pain (Fig. 109.10).⁷⁸ If the skeletal age of the patient is immature (cartilaginous or apophyseal stage), subsequent slippage (isthmic spondylolisthesis) can develop (*see* Fig. 109.1).² Careful management of patient, especially if female, is therefore required.⁷⁹

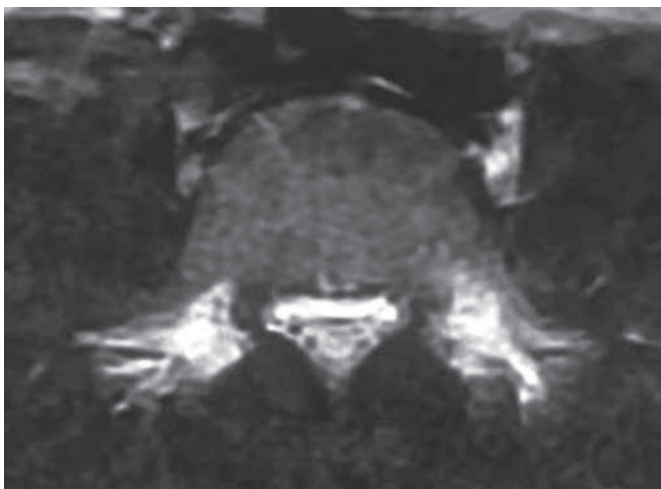


Fig. 109.9: Signal change defined as high-signal change (HSC) on fat saturation sequences. HSC is visible in the bilateral pedicles at L5.

Table 109.1: Union rate and duration to achieve bony healing according to the CT and MRI classification.⁷⁶

Parameter	CT stage			
	Progressive			
	HSP		No HSP	
	Early	on MRI	on MRI	Terminal
No. of defect	33	11	11	8
Union	31	7	3	0
Union rate (%)	94	64	27	0
Duration until union (mos)	3.2	5.4	5.7	NA

(HSP: High signal change at the adjacent pedicle; NA: Not applicable; CT: Computed tomography; MRI: Magnetic resonance imaging).

Surgical Treatment

Surgical treatment should be indicated only for patients with a mature spine and terminal-stage spondylolysis causing persistent and severe low back pain and/or leg pain. For pediatric patients with an immature spine, surgery is not recommended. To treat low back pain caused by painful spondylolysis, direct repair of the pars defects is performed. Several techniques have been reported, including screw placement into the defects (Buck's technique),^{80,81} the wiring method,⁸² and the pedicle screw and hook method.⁸³ In some patients, radiculopathy can be combined with lumbar spondylolysis. The main lesion compressing the nerve root is usually at the proximal portion of the spondylolysis and is known as the ragged

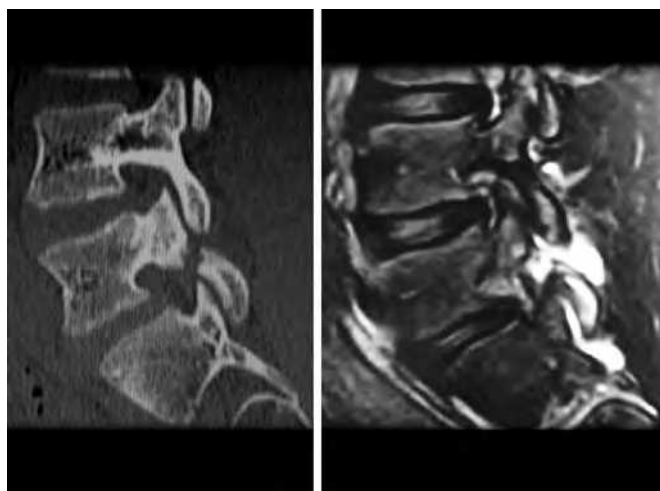


Fig. 109.10: Computed tomography showing terminal-stage bilateral L5 spondylolysis. Short T1 inversion recovery—magnetic resonance imaging of a 14-year-old male soccer player clearly indicating effusion at the defect and both adjoining facet joints.

edge of the lysis. Therefore, nerve root impingement can be decompressed with an endoscope to treat this radiculopathy.⁸⁴

Spondylolisthesis

Spondylolisthesis is subdivided into five subtypes: isthmic, degenerative, dysplastic, congenital, and traumatic. The isthmic type is caused by a defect in the pars interarticularis, called spondylolysis, pars defect, or pars fracture, and, along with the degenerative type, is one of the two most common forms of spondylolisthesis. Isthmic spondylolisthesis is thought to occur in children and adolescents based on epiphyseal separation, which is due to a physeal stress fracture of the vertebral body.⁸⁵ Therefore, slippage progression in isthmic spondylolisthesis usually occurs during the growth spurt and is minimal after skeletal maturity.² On the other hand, it is well known that the pathogenesis of degenerative spondylolisthesis is associated with disc degeneration, followed by facet laxity and ligamentum flavum hypertrophy, which results in spinal canal stenosis. Therefore, degenerative spondylolisthesis is common in those aged over 40 years. As mentioned above, isthmic spondylolisthesis involves subsequent slippage of spondylolysis. Slippage is more prevalent in individuals with a younger skeletal age whose spine is immature, and slippage is halted when the growth period is over and the vertebrae have matured.² Therefore, only isthmic spondylolisthesis is focused on in this chapter.

Clinical Presentation

In isthmic spondylolisthesis, low back pain is a common initial symptom. Some patients have radiculopathy in the lower extremities caused by fibrocartilaginous proliferation around the pars defect. This radiculopathy affects the exiting nerve root associated with the cephalad vertebra of the involved spinal segment. Most cases of L5 spondylolysis involve the L5 nerve root. Thus, typical symptoms of isthmic spondylolisthesis are low back pain due to spinal instability and radiating leg pain due to the compressed exiting nerve root. Furthermore, in isthmic spondylolisthesis, pseudodisc bulging is easily identified.

Surgical Treatment

Most patients who develop isthmic spondylolisthesis are asymptomatic. In adolescents with symptomatic isthmic spondylolisthesis, pain relief is achieved in approximately 70% of cases after conservative therapy,⁸⁶ which includes administration of NSAIDs, selective nerve blocks, injections into the pars defect, brace therapy, restriction of sports activities, and occasionally bed rest. Moreover, indications for surgical treatment in patients with an immature spine must be carefully considered after taking into account skeletal age, severity of symptoms, and degree and progression of instability.

Low-grade Spondylolisthesis (Grade I or II)

Noninstrumented fusion: A retrospective study with a long-term follow-up (mean: 19.7 years) of uninstrumented posterolateral spinal arthrodesis in 49 adolescents with grade I or II lumbar isthmic spondylolisthesis showed an outcome of good spinal fusion in 43 (87.7%) patients who attained solid fusion and pseudarthrosis in six patients (12.3%).⁸⁷ Satisfactory results were obtained in 94% of patients, and these outcomes were closely associated with the rate of successful fusion.

Instrumented fusion: Numerous operative procedures have been described for isthmic spondylolisthesis including posterolateral fusion (PLF) with or without decompression, possibly with spinal instrumentation and possibly including anterior lumbar interbody fusion, posterior lumbar interbody fusion, transforaminal lumbar interbody fusion, and circumferential anterior and posterior fusion. However, for patients with an immature spine, indication of these surgical treatments is controversial because the effect of spinal growth on the outcome of

lumbosacral spinal fusion remains unclear, although remodeling of the fusion area has been noted to decrease slippage in younger children.⁸⁸ A recent long-term follow-up study following surgical treatment for isthmic spondylolisthesis in a significant number of adolescents and children who underwent surgery before the pubertal growth spurt was reported by Jalanko et al.⁸⁹ Their results showed satisfactory outcomes in both groups, and patients who underwent surgery during or before the pubertal growth spurt had a statistically better outcome in low back pain scores compared with adolescents at the final follow-up.

High-grade Spondylolisthesis (Grades III, IV, or V)

High-grade isthmic spondylolisthesis comprises a distinct minority of all patients with spondylolisthesis, but treatment of these high-grades of spondylolisthesis can be complex and difficult, and the optimal treatment of this pathology remains controversial. The clinical indications for surgical treatment of high-grade spondylolisthesis include continued pain despite conservative treatments, spinal deformity progression, and neurological symptoms. Most patients with high-grade spondylolisthesis or spondyloptosis—which is complete subluxation of the cephalad vertebra from the lower vertebra classified as a grade V spondylolisthesis—become symptomatic during adolescence. A recent literature review on surgical treatment for high-grade spondylolisthesis in the pediatric population concluded that it was impossible to formulate clear guidelines for the treatment of high-grade spondylolisthesis based on the best evidence available in the published literature because of the paucity of high-level studies available on this topic.⁹⁰ Many studies focusing on a reduction in high-grade spondylolisthesis have been performed. An L5 vertebrectomy and reduction of L4 onto S1 as surgical treatment for fixed spondyloptosis was described by Gains.⁹¹ The most widespread reduction method for high-grade spondylolisthesis is posterior decompression, reduction, and fusion with placement of segmental spinal instrumentation.⁹² Another option for the treatment of adolescent spondyloptosis is the use of an external fixation device.⁹³

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SECTION

12

Adult Deformity

Alexander R Vaccaro

Sacro pelvic Morphology and Spinopelvic Alignment

Alexander J Schupper, Justin K Scheer, Justin S Smith, Benjamin Blondel, Virginie Lafage, Frank Schwab, Christopher P Ames

Snapshot

- » Sacropelvic Morphology
- » Spinopelvic Alignment
- » Global Spinopelvic Alignment Relationships
- » Importance of Spinopelvic Parameters in Surgical Planning

INTRODUCTION

Management of spinal deformity includes recognition and treatment of scoliotic, kyphotic, and spondylolisthetic conditions. Historically, treatment has focused upon scoliosis correction and prevention of scoliotic curve progression; however, recent data has demonstrated the impact that sagittal plane deformities and global spinal alignment have in the generation of pain and disability. Consequently, increased emphasis has been placed upon restoring physiologic lumbar lordosis (LL), thoracic kyphosis (TK), and the C7 plumb-line [sagittal vertical axis (SVA)]. The spinopelvic relationship has been less frequently evaluated when treating spinal deformities. The position of the pelvis plays a critical role in maintaining upright, sitting, and standing postures by acting as an intercalary unit between the spine and the lower extremities.^{1,2} Failure to account for pelvic alignment when treating spinal deformity increases the risk of spinal malalignment, and subsequent long-term decompensation, resulting in treatment failure. Furthermore, a paradigm shift is emerging in which the spine is being studied as a whole, with alignment relationships extending from the pelvis to the cervical spine. Recent studies have shown that regional spinal parameters are not independent of one another and have a large impact on other areas of the spine, including the pelvis.³ This chapter will review the spinopelvic parameters needed to evaluate adult spinal deformities and the implications these measures have for treatment.

SACROPELVIC MORPHOLOGY

There has been increasing recognition of the important role of the pelvis in spinal alignment.⁴⁻¹⁸ The most commonly assessed radiographic measures of sagittal spinopelvic alignment include pelvic incidence (PI), pelvic tilt (PT), and sacral slope (SS). Pelvic incidence is defined as the angle subtended by a line drawn between the center of the femoral head and the sacral endplate and a line drawn perpendicular to the center of the sacral endplate (Fig. 110.1).^{12,19} Pelvic incidence is a morphologic parameter that remains consistent during the patient's lifetime, with slight changes occurring during prepubertal development. Following puberty, PI is generally considered to be a fixed, morphologic parameter, reflecting the relationship of the sacrum to the pelvis. Pelvic tilt is defined as the angle subtended by a line drawn from the midpoint of the sacral endplate to the center of the bicoxofemoral axis and a vertical plumb line extended from the bicoxofemoral axis (Fig. 110.2).¹⁹ Sacral slope is defined as the angle subtended by a line drawn along the endplate of the sacrum and a horizontal reference line extended from the posterior superior corner of S1 (Fig. 110.3).¹⁹ It has been previously established that these parameters are correlated and are predictive of the ideal LL (large PI requires a large LL),^{5,12} thus creating a spinopelvic chain of correlation in adult volunteers.^{16,20} A mathematical relationship exists such that the PI is the sum of the PT and SS ($PI = PT + SS$).^{12,19} As the PT increases, the SS decreases due to the sacrum assuming a more

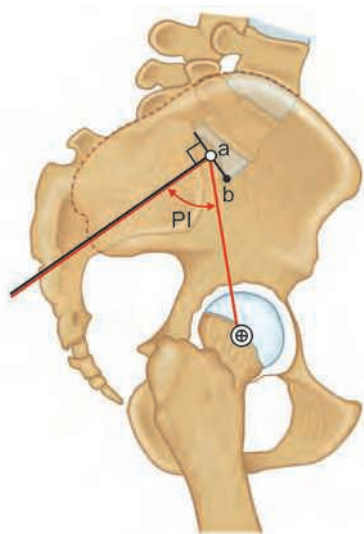


Fig. 110.1: Diagram showing the measurements of pelvic incidence (PI).

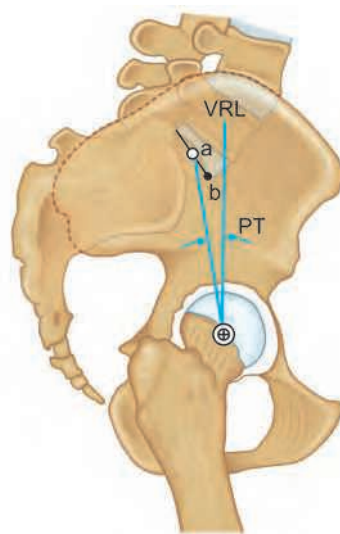


Fig. 110.2: Diagram showing the measurements of pelvic tilt (PT). (VRL: Vertical line).

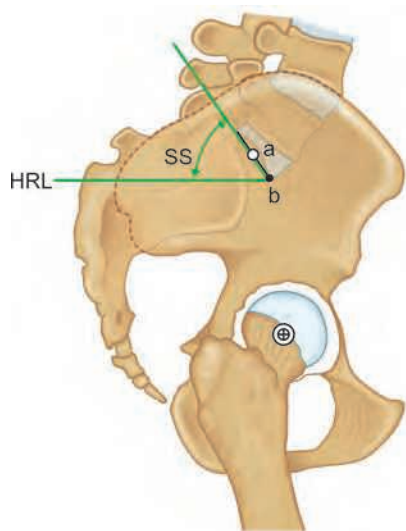


Fig. 110.3: Diagram showing the measurements of sacral slope (SS). (HRL: Horizontal line).

vertical position about the femoral head axis (pelvic retroversion). Pelvic retroversion is a compensatory mechanism used to sagittally rebalance the spine and maintain upright posture in cases of sagittal spinal misalignment (SSM) (e.g. compensate for decreased LL). Normal gait requires forward flexion of the pelvis. If the pelvis is retroverted (high PT) during gait, the hip joint is externally rotated. Therefore, the knee joints internally rotate to compensate for the abnormal hip position.^{21,22}

Just as PT and PI must be considered preoperatively to achieve global spinal alignment in the sagittal plane, pelvic obliquity or coronal plane pelvic deformity and associated etiology should be considered in the coronal plane correction strategy. Pelvic obliquity is quantified by measuring the angle formed between a horizontal reference line and a line drawn between the two inferior points of the sacral ala on an anteroposterior X-ray (Fig. 110.4).

Pelvic obliquity due to leg-length discrepancy from congenital or acquired conditions (e.g. hip or knee osteoarthritis, prior arthroplasty) or from sacropelvic deformity may produce a compensatory lumbar curve to balance the spine. Correction of this lumbar curve without correction of the primary driver of the pelvic obliquity may lead to coronal decompensation. In other cases, the pelvic obliquity may be secondary (attempting to compensate) to the spinal scoliotic curve, and curve-correction strategies must be of sufficient magnitude to allow the pelvis to relax in the coronal plane. Surgical planning with regard to pelvic obliquity is discussed further.

■ SPINOPELVIC ALIGNMENT

Concept of Cone of Economy

The ability to effectively maintain a standing upright posture is fundamental to normal human function. Spinal deformities often impair the ability to maintain upright posture. Recent studies of patients with spinal deformity

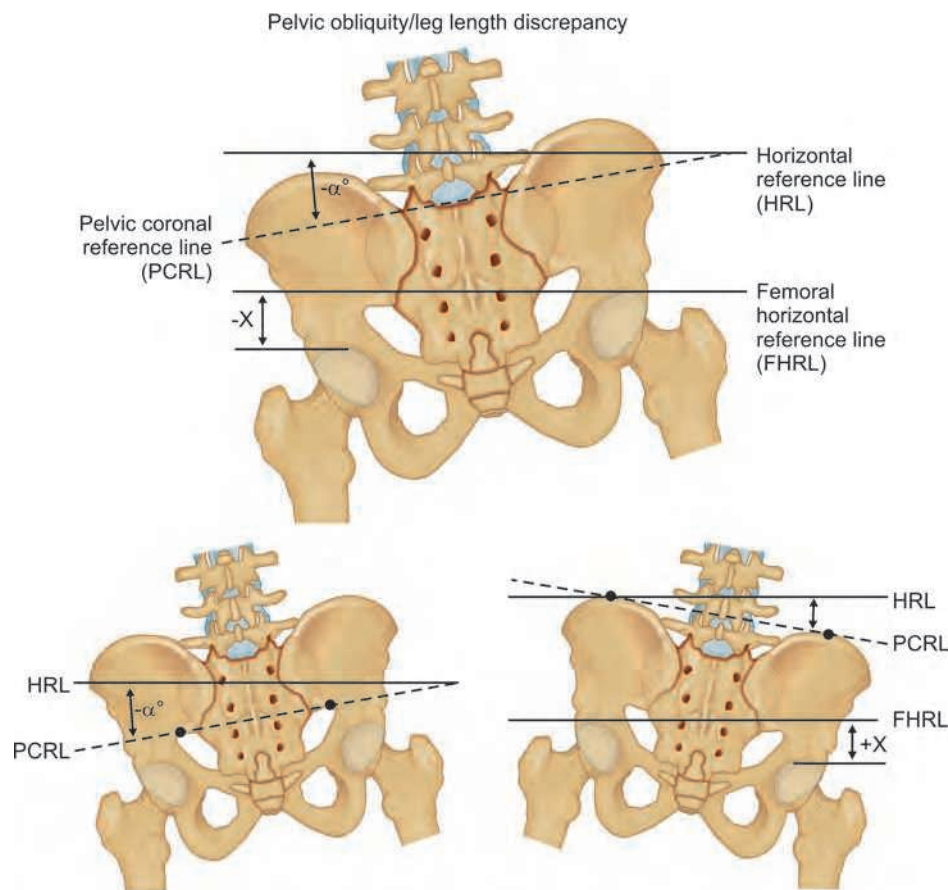


Fig. 110.4: Method for measuring pelvic obliquity.

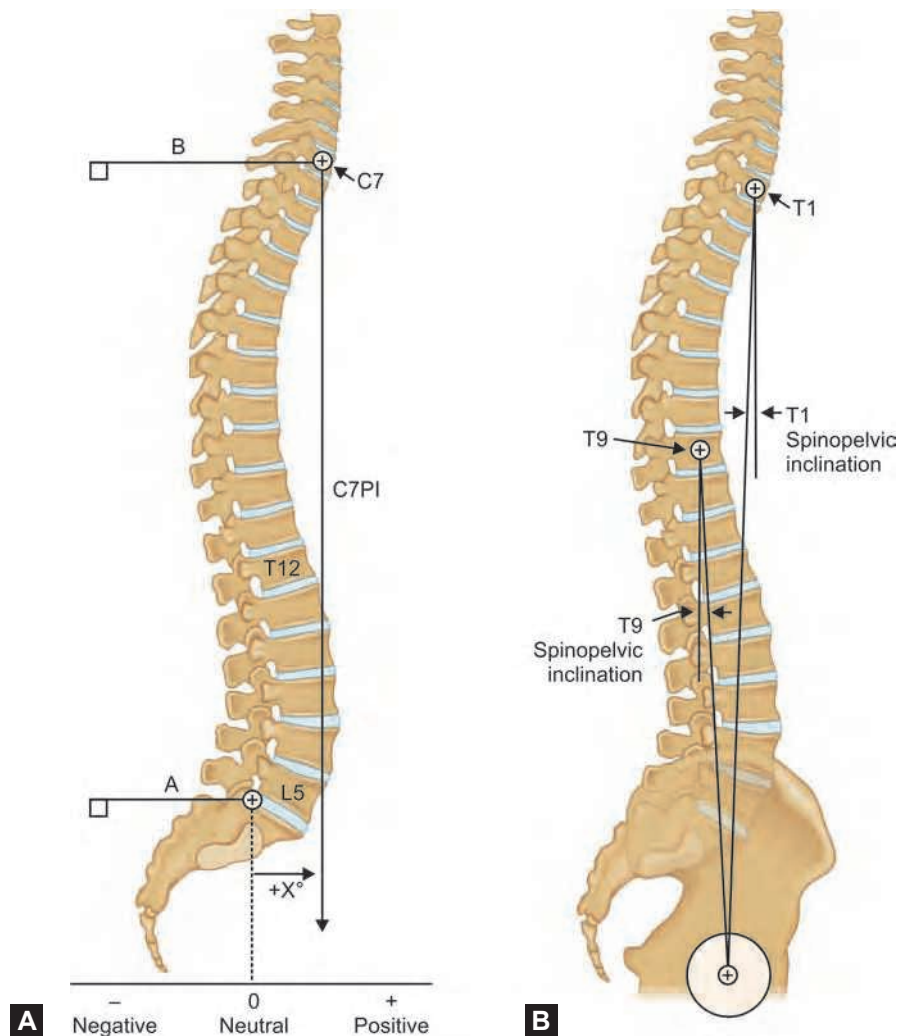
have demonstrated that global spinal malalignment is a strong predictor of disability.^{10,23-25} Despite the importance of posture and balance to human function, the defining and impacting factors remain incompletely understood.¹⁶

Dubousset introduced the concept of a “cone of economy” to describe the fundamentals of optimal standing balance and posture.²⁶ This concept is based on a cone, centered at the feet of a standing individual, which projects upward and outward. This cone defines the range of standing postures for which the body can remain balanced with minimal effort and free from external support. In essence, the cone is defined by the range of sway of the center of mass, relative to the feet, that can be readily accommodated by the structural elements and musculature of the standing individual. As the body moves toward the periphery of this cone, additional effort and energy expenditure are necessary to maintain balance. Beyond the perimeter of the cone, external support, such as a cane, crutch, or walker, may be necessary to prevent the individual from falling.

The substantially greater energy that is required to maintain unsupported standing posture that approaches the periphery of the “cone of economy” or beyond can produce fatigue, pain, and disability.²⁶ Several radiographic measures have been defined for the assessment of spinal alignment in addition to the pelvic parameters discussed earlier; including coronal and sagittal measures.

Assessment of Sagittal Alignment

Multiple parameters are used to describe sagittal alignment (SA). The most common measure of global SA is the SVA, which is assessed on lateral 36-inch standing radiographs. Sagittal vertical axis is defined as the horizontal offset between the C7PL and the posterior superior aspect of the S1 vertebral body (Fig. 110.5A). Positive and negative values of SVA reflect cases in which the C7PL falls anterior or posterior to the posterior superior corner of the S1 vertebral body, respectively (Fig. 110.5A). The T1 spinopelvic inclination²⁷ (T1SPI) and the T9 spinopelvic

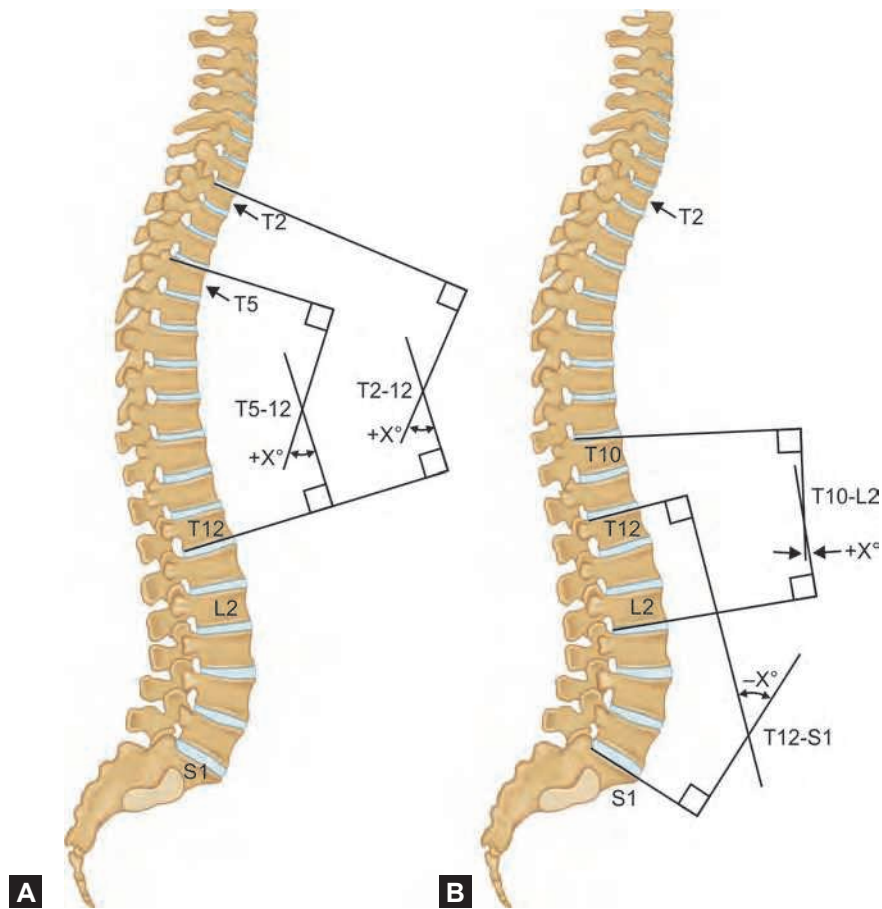


Figs. 110.5A and B: Measurement parameters for spinal sagittal alignment (A). The sagittal vertebral axis is measured as the distance from the posterior superior corner of the sacrum to a vertical plumb line dropped from the C7 centroid shown as +X (B). Spinopelvic inclination (SPI) is a global angular measurement of sagittal alignment. The SPI is the angle formed by a line from the femoral heads to the T1 or T9 centroid and the vertical plumb line. Because this is an angle rather than a length measurement, it is not subject to magnification variability in X-ray.

inclination (T9SPI) are alternative measures of SA. These measures are angles between the vertical plumb line extended from the bicoxofemoral axis and lines drawn from the vertebral body center of T1 or T9 to the center of the bicoxofemoral axis (Fig. 110.5B). As the T1 and T9 inclination are angles rather than measured lines, they are not prone to radiographic magnification issues. Sagittal alignment is also assessed through regional measures of thoracic and lumbar alignment, including Cobb angles of TK (T2–T12, T2–T5, and T5–T12; Fig. 110.6A), thoracolumbar kyphosis (TLK; T10–L2), and LL (T12–S1; Fig. 110.6B).

Assessment of Coronal Alignment

Coronal alignment (CA) is assessed using 36-inch standing radiographs. The CA is the horizontal distance between the C7 plumb line (C7PL)—a vertical line dropped from the middle of the C7 vertebral body—parallel to the lateral edge of the film, and the central sacral vertical line (CSVL), which is the vertical line in a coronal radiograph that passes through the center of the sacrum (Fig. 110.7). A CA of zero is designated as “neutral”. Malalignments to the left or right of the neutral line are designated as negative or positive distances, respectively.



Figs. 110.6A and B: (A) Diagram showing the method for measuring thoracic kyphosis. Typically, thoracic kyphosis is measured from T5 to T12 as, often, the T2 endplate is difficult to visualize. (B) Diagram showing the method for measuring lumbar lordosis. Lumbar lordosis is generally measured from T12 to S1 ($-X$) and thoracolumbar alignment from T10 to L2 ($+X$).

Normal Values of Spinopelvic Alignment

The normal value of CA is zero, as the spine should be vertically straight in the frontal plane; therefore, the C7 should be aligned centrally over the sacrum. The normative values for sagittal spinopelvic parameters are less concisely defined, and often are dependent on age.^{5,12,16,28-31} With increasing age, SVA, T1SPI, T9SPI, TK, and PT tend to increase, whereas LL tends to decrease with age.^{5,12,16,28,30,31} Normative spinopelvic values have been reported in an adult volunteer population by age groups and are listed in Table 110.1.³

GLOBAL SPINOPELVIC ALIGNMENT RELATIONSHIPS

The spinal regions (pelvis, lumbar, thoracic, and cervical) are not independent of one another and multiple significant correlations have been found between them,³

consistent with the described necessity to preserve a neutral SA as reported by Kuntz et al.³² A recent study³ investigated all spinal parameters in an asymptomatic volunteer population with a mean age of 45 (range, 20–77). Following an extensive analysis, the authors found that PI correlates with LL, LL correlates with TK, and TK correlates with CL (Fig. 110.8).³ Thus, an increase in PI correlates with an increase in LL, which correlates with an increase in TK, which then correlates with an increase in CL.³ However, there was a lack of correlation found between PI and TK, making the chain of correlation from the pelvis to the cervical spine more complicated. The current view is that LL is proportional to PI and TK because PI is a fixed parameter and TK has little flexibility. Subjects with a small PI or small TK had smaller LL than subjects with small PI and large TK. This demonstrates that TK is not a result of LL, but rather, LL is a result of TK and PI. As mentioned earlier, CL was correlated with TK showing that, as TK

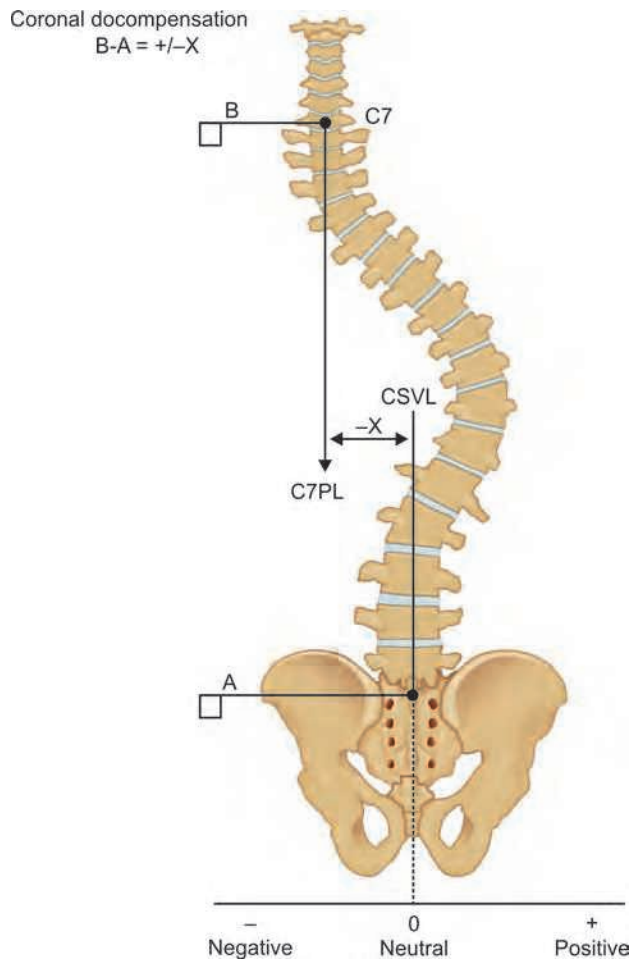


Fig. 110.7: The distance between the C7 plumb line (C7PL) and the central sacral vertical line (CSVL) defines the amount of coronal plane decompensation in centimeters (termed $-X$ in this picture).

increases, CL also increases. However, this change in CL is not large enough to maintain the head over the pelvis, but it does provide adequate maintenance of horizontal gaze. In addition to the correlations between CL and TK, CL was also found to correlate with the SVA, PT (Fig. 110.9), and T1 slope.³ Subjects that had a positive SVA demonstrated an increase in cervical lordosis, regardless of whether their SVA was within the normal range of values. This cervical adaptation to the sagittal global alignment is a compensatory mechanism in order to maintain a horizontal gaze as mentioned earlier. Therefore, cervical lordosis can be considered, similar to TK and LL, as an adaptive spinal mechanism to maintain global alignment. When LL and TK are adapted to the patient's pelvic incidence, the amount of cervical lordosis will be proportional to the other curves. However, when the patient has an anterior malalignment of the spine (from a reduction in LL and/or an increase in TK), an increase in cervical lordosis is a compensatory mechanism. Conversely, if a primary cervical deformity exists, changes in the lumbar spine and pelvis will attempt to compensate.

■ IMPORTANCE OF SPINOPELVIC PARAMETERS IN SURGICAL PLANNING

Health-related quality of life (HRQOL) scores following surgery for adult spinal deformity are strongly correlated with the achievement of sagittal and coronal spinal alignment.^{33,34} Traditionally, SVA and C7-CSVL offset have been used to assess sagittal and coronal alignments,

Table 110.1: Mean sagittal parameters among the volunteers stratified by age group.³

	20–39 years		40–59 years		> 60 years		P value
	Mean	SD	Mean	SD	Mean	SD	
C2–C7 cervical lordosis (°)	+9.4	9	+6.6	9	+22.2*	9	< 0.001
T4–T12 thoracic kyphosis (°)	–38.1	11	–36	9	–45	14	NS
L1–S1 lumbar lordosis (°)	+61.5	12	+60.3	7	+55.7	13	NS
Pelvic tilt (°)	12.1	7	14.5	5	15.1	8	NS
Pelvic incidence (°)	52.1	10	54.3	8	53.5	10	NS
Sacral slope (°)	40	9	39.9	7	36.5	10	NS
SVA (mm)	–28.5	28	–18.2	39	22.4*	40	< 0.001
T1 slope (°)	–22	7	–21.1	8	–31.6*	9	0.001

NS: Nonsignificant; * $P < 0.05$.

P values refer to ANOVA comparison between groups.

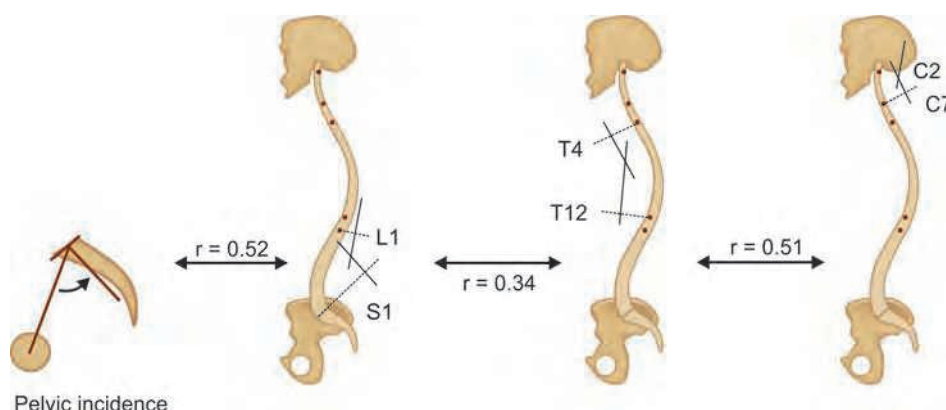


Fig. 110.8: Chain of correlation between PI and regional sagittal parameters with the corresponding Pearson coefficient r values. A large PI requires a large lumbar lordosis. An increase of lumbar lordosis is correlated with an increased thoracic kyphosis, which is correlated with an increased cervical lordosis.

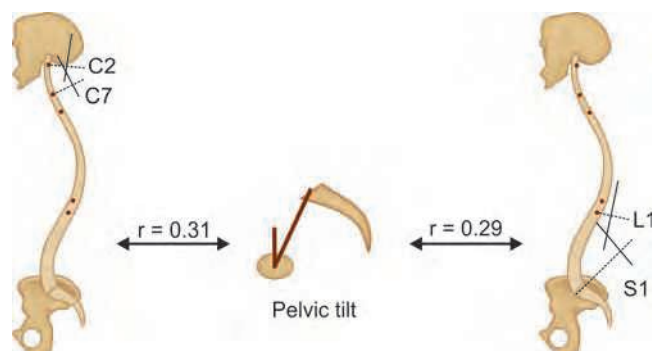


Fig. 110.9: Correlation between pelvic tilt and lumbar/cervical lordosis. A loss of lumbar lordosis is correlated with a pelvic retroversion acting as compensatory mechanisms. Pelvic retroversion is also correlated with an increased cervical lordosis.

respectively, with the goal of corrective surgery to achieve $SVA < 4$ cm and $CA < 4$ cm. Recently, however, Lafage et al. reported that T1SPI more accurately correlated with HRQOL scores than SVA.¹⁰ The authors also reported that increased PT values were reflective of pelvic retroversion and correlated with worsening HRQOL scores.¹⁰ Accordingly, Schwab et al. used normative data and postoperative HRQOL measures to evaluate the maximal amount of tolerable sagittal and coronal spinal malalignment in order to provide radiographic alignment guidelines for spinal reconstructive procedures.³⁵ Based on the evaluated data, the authors reported that the goal of spinal realignment procedures should be: $SVA < 50$ mm, $T1SPI < 0^\circ$, and $PT < 20^\circ$.³⁵ Additionally, the authors emphasized evaluating the pre- and postoperative relationships between LL and PI as an assessment of spinopelvic harmony. The ideal

relationship that was consistent with normative data and correlated with good postoperative HRQOL scores was $LL = PI \pm 9^\circ$.³⁵

In an attempt to optimize postoperative SA, several authors have proposed mathematical formulas to aid surgical planning. These formulas vary in the amount of complexity, as some formulas simply provide a target postoperative LL:TK relationship, whereas others estimate the degree of osteotomy resection needed to restore SA. Ondra et al. used a trigonometric methods to calculate the angle of correction needed to achieve neutral alignment for pedicle subtraction osteotomy (PSO) procedures.³⁶ One shortcoming of this method, however, is that the contribution of the pelvis to SA is neglected. As indicated earlier, the amount of LL required to restore physiologic SA is not the same for every spine, but instead, varies with PI. Additionally, patients increase PT to compensate for global spinal malalignment. This compensatory increase in PT results in increased energy expenditure contributing to greater disability.¹⁰ For patients that have SSM and increased PT, normalization of PT requires greater angular correction³⁷ than predicted by Ondra's technique. This shortcoming must be recognized, as patients with severe SSM are at risk of under-correction if the magnitude of the spinopelvic deformity is not recognized and a single level PSO is carried out.³⁸ If greater sagittal correction is needed, a variety of methods can be employed to supplement the correction generated by the PSO, including adjacent-level interbody grafting combined with Ponte-type osteotomy. Another option may be to combine two types of three column osteotomies in order to achieve optimal coronal and SA.

Another important consideration when planning spinal reconstructive procedures is that the spinal segments that are not incorporated into the fusion may change alignment, which, in turn, can significantly impact the achievement of optimal postoperative spinal alignment. Lafage et al. reported on the negative impact that an increased TK following lumbar PSO has upon postoperative SA.³⁹ The patients in this study developed a reciprocal increase of 13° of TK within the nonfused thoracic spine after lumbar PSO.³⁹ This increase in TK resulted in poor postoperative spinal alignment in 18/34 study patients.³⁹ This phenomenon is more common in patients with higher PI, greater preoperative SSM, and older age, with an average age of 59 years old.³⁹

Currently, the amount of reciprocal thoracic change cannot completely be predicted preoperatively. Prediction of such unfavorable thoracic reciprocal changes is difficult for the following two reasons: (1) the preoperative assessment of TK may be inaccurate due to the anterior malalignment, and (2) patients with an increased sagittal vertical axis tend to reduce their TK by muscular contracture in order to maintain the head over the pelvis. However, one can look to the patient's morphology (in addition to the three parameters discussed earlier: high PI, large SSM, and older age), to attempt a prediction. Roussouly and Nnadi⁴⁰ describe a classification system (types 1–4) of patients based on their SA morphologic characteristics. In this system, patients are classified based on their length ratios of the thoracic kyphotic curvature to lumbar lordotic curvature with type 1 through type 4 being 80:20, 60:40, 50:50, and 20:80 respectively.⁴⁰ Thus, patients that are classified as type 3 are well balanced, whereas patients classified as type 4 have a large PI, long LL, and a short and pronounced TK (ratio 20:80). Type 4 patients may be at a higher risk of postoperative unfavorable reciprocal thoracic changes than type 3 patients.

When deciding on the location of an osteotomy, current thinking places the greatest importance on the location of the osteotomy, which impacts the amount of translational correction that can be gained. The lower a 30° osteotomy is placed in the lumbar spine, the more impact it has on plumb-line correction. Larger angular corrections are needed in superior locations in the spine to affect the same translational shift in the plumb line compared to osteotomies located in the caudal locations of the spine.

However, recent work by Lafage et al. has shown that the osteotomy location may not be as critical.⁴¹ Based on the level of the osteotomy, there was no difference in the

focal correction and no correlation with SVA correction.⁴¹ Preoperative PT and unfavorable thoracic reciprocal changes must be accounted for in calculating the amount and location of correction angle needed for optimal alignment. More caudal osteotomies in the lumbar spine were significantly correlated with greater PT reductions and the degree of osteotomy was significantly correlated with changes in TK.⁴¹ The ideal alignment accounts for a relaxed thoracic spine and a normal PT as well as optimal SVA.

Patients with elevated SVA and low PT (lack of pelvic compensation for a high SVA) represent a distinct subgroup of patients in whom attempted operative correction is subject to greater risk of postoperative failure. This pattern may be seen in (1) patients with pre-existing hip flexion contracture, (2) degenerative flatback patients with primary extensor muscle pathology,⁴² (3) globally decompensated patients with secondary extensor muscle weakness, and (4) patients leaning forward to compensate for severe lumbar stenosis. All patients in whom corrective surgery is being considered should undergo evaluation to rule out hip flexion contracture. Typically, the Thomas test is performed with the patient supine, with the leg bent and pressed against the lower torso, while monitoring the contralateral leg for signs of knee flexion. Patients with mild extensor muscle weakness may be referred for hip-extensor-strengthening physical therapy preoperatively.

Lee et al. advocated the separation of degenerative flatback patients into those that are able to maintain PT when ambulating and those that tilt forward and are unable to maintain their PT when walking.⁴² Gait studies have demonstrated significant abnormalities in patients with postoperative sagittal malalignment, and this is likely related to the fact that patients incline their pelvis forward when walking. If pelvic retroversion is being used to maintain standing balance, this compensatory mechanism will be maintained during walking, thus placing the pelvis in a nonphysiologic position. The ability to maintain this pelvis retroversion while walking demonstrates adequate pelvic extensor muscle strength but comes at the cost of increased energy expenditure, hip external rotation, and knee internal rotation in gait analysis studies.²²

Given the importance of achieving spinal pelvic harmony and the frequent occurrence of unfavorable reciprocal changes after corrective surgery, several formulas for prediction of ideal postoperative SVA have been developed.^{15,43,44} The predictive accuracy of these formulas has recently been analyzed in a large PSO database.⁴⁵

Table 110.2: Accuracy of mathematical formulas to predict good and poor postoperative sagittal alignment following single-level PSO.

<i>Author and year</i>	<i>Mathematical formula</i>	<i>Accuracy prediction good post-operative SVA (% correct)</i>	<i>Accuracy prediction poor postoperative SVA (% correct)</i>	<i>Total prediction accuracy (good and poor post-operative SVA; % correct)</i>	<i>Prediction accuracy (good and poor postoperative SVA; Spearman's coefficient)</i>	<i>Mean error SVA prediction (mm)</i>
Scwab et al., 2009	$LL \geq PI - 10^\circ$	78	79	78	0.55	NA
Kim et al., 2006	$LL \geq TK + 20^\circ$	51	87	63	0.37	NA
Ondra et al., 2006	PSO angle = $\text{atan}(y/z)$	59	98	72	0.54	111
Rose et al., 2009	$LL + PI + TK \leq 45^\circ$	97	28	74	0.37	NA
Lafage et al., 2011	$SVA = -52.87 + 5.90(PI) - 5.13(LL_{\max}) - 4.45(PT) - 2.09(TK_{\max}) + 0.57(\text{age})$	98	70	89*	0.75*	30

* $P < 0.05$.

(LL: Lumbar lordosis; LL_{\max} : Maximum lumbar lordosis; PI: Pelvic incidence; PSO: Pedicle subtraction osteotomy; SVA: Sagittal vertebral axis; TK: Thoracic kyphosis; TK_{\max} : Maximum thoracic kyphosis).

The most accurate formulas include PI and PT as well regional spinal curvatures including TK and LL in the Lafage formula (Table 110.2).^{15,36,45, 46-49}

Pelvic Obliquity and Scoliosis Correction

As mentioned earlier, pelvic obliquity may be a result of a leg-length discrepancy from congenital or acquired conditions (e.g. hip or knee osteoarthritis, prior arthroplasty) or from sacropelvic deformity, which may produce a compensatory lumbar curve to balance the spine. All patients should be evaluated clinically and radiographically for a leg-length discrepancy and, if identified, re-evaluated after fitting with a shoe lift to assess how the spine and pelvis respond to correction of the leg-length discrepancy both clinically and radiographically. This can be done by obtaining a standing anteroposterior pelvic X-ray with subsequent lower extremity scanograms if the pelvis is found to be uneven. Patients with a flexible curve secondary to a pelvic obliquity due to a leg-length discrepancy may respond well to the addition of a shoe lift only or surgical treatment of the leg-length discrepancy. If the spinal curve is rigid, it will not correct after the addition of a shoe lift. In this case, there are two options: (1) to correct the curve perpendicular to the oblique pelvis and ignore the pelvic obliquity and (2) to correct the spine to a level pelvis if leg-length correction is planned (e.g. with a future hip replacement) or the patient tolerates a shoe lift (Fig. 110.10).

Prediction of ideal curve correction in the setting of double major curves and curve patterns with lumbosacral fractional curves can be quite challenging. Careful study of the preoperative side of malalignment will determine the magnitude of the curve corrections possible while maintaining standing global coronal balance. Often, the fractional curve may allow rebalancing of the spine via small angular coronal corrections at the lumbar sacral junction. Comparison of preoperative standing and prone films may assist the surgeon in estimating the anticipated difference in alignment likely to be seen on the operative table and, therefore, the likely magnitude of optimal curve correction. Preoperative bending films will also assist the surgeon in determining how much correction may occur if a curve is not included in the fusion. Intraoperative full-cassette films should be obtained and interpreted with an understanding of the patient's baseline pelvic malalignment. These are obtained by placing the long film plate on a stool underneath a radiolucent table for anterior-posterior imaging and by placing the long cassette on a film holder lateral to the patient. The global sagittal plane is more accurately assessed than the global coronal plane, in general, because leg-length discrepancies that mainly impact the coronal plane are not easily assessed until the patient stands in the early postoperative period. Thus, as it is often difficult to predict how the patients with complex curve patterns and pelvic obliquity will correct when standing, early

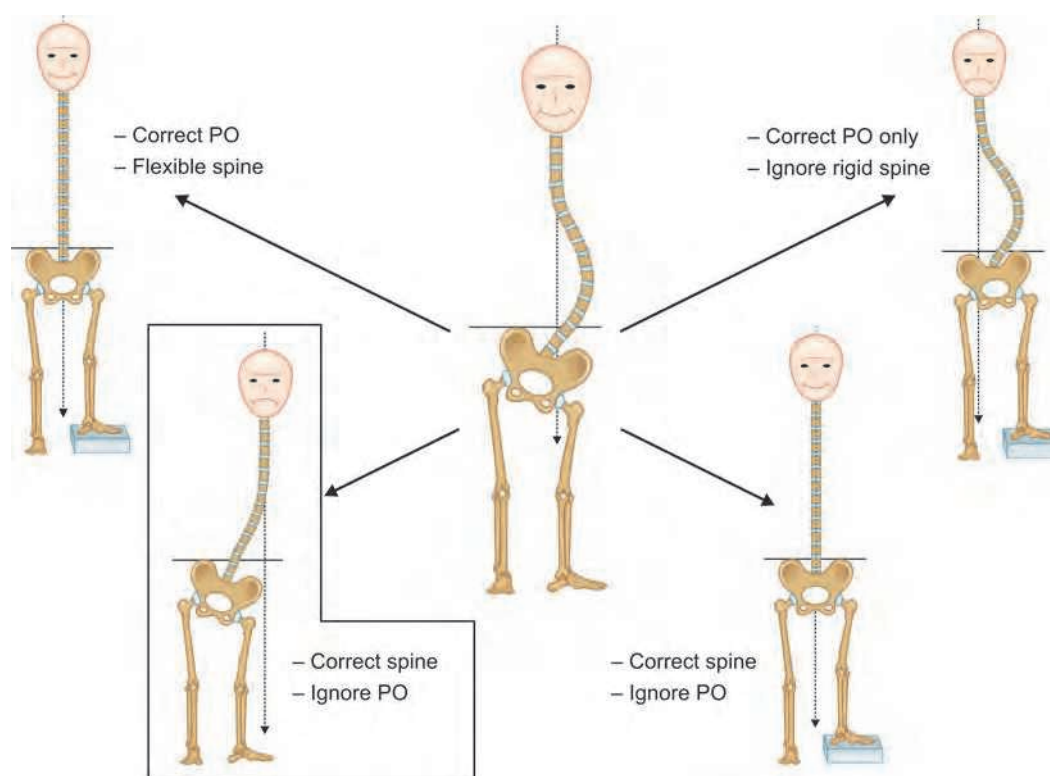


Fig. 110.10: Artist diagram displaying a general algorithm for treatment of patients with scoliosis, coronal malalignment, and pelvic obliquity. In patients with pelvic obliquity in which the spine is flexible and aligned, full correction of the curve may lead to significant coronal decompensation as the scoliotic curve may be compensatory. In some of these patients, the addition of a shoe lift will allow the flexible spine to relax and may improve alignment and deformity-related symptoms. If the spine is rigid as is more common in adults, a shoe lift may be poorly tolerated and may not be effective in rebalancing the spine. These patients may require incomplete curve corrections and, sometimes, a shoe lift as well depending upon the final standing alignment. (PO: Pelvic obliquity).

postoperative standing films are further recommended to allow further coronal adjustments if needed. The patient's ability to compensate for rigid coronal malalignment is even less than for sagittal malalignment as no direct correlate exists for pelvic retroversion in the coronal plane.

SUMMARY

The pelvis plays a critical role in upright balanced sitting and standing postures, and recent data demonstrate that failure to account for pelvic alignment when treating spinal deformity increases the risk of residual spinal deformity and long-term treatment failure. Pelvic alignment including PI, PT, SS, and pelvic obliquity must be evaluated by treating physicians in addition to more traditional measures such as SVA, LL, TK, and regional scoliotic curves. Particular attention must be paid to PT, which is a dynamic pelvic parameter reflective of pelvic retroversion, as increased PT implies residual postoperative spinal

deformity and will negatively affect function and, thus, postoperative outcomes.

When planning for spinal reconstructive procedures, it is important to consider that preoperative planning formulas that do not evaluate pelvic parameters, especially PI and PT, may be inaccurate and increase the risk of postoperative malalignment. Normalization of the PT requires more angular correction than predicted by the Ondra formula. Preoperative planning formulas such as the one developed by Lafage et al. that include PI, PT, LL, TK, and patient age are the most accurate.⁴⁷ The location of the osteotomy along the spine is also an important consideration when attempting to normalize the PT, as a more caudal osteotomy is associated with greater PT reduction. It is also important to consider that spinal segments not incorporated within the fusion may increase kyphosis after lumbar PSO. These unfavorable changes are more common in patients with higher PI, greater preoperative SSM, and older age.

Pelvic obliquity and the associated etiology must be accounted for in strategies for coronal plane correction. Correction of lumbar curve in the setting of pelvic obliquity may generate postoperative coronal decompensation. If the pelvic obliquity is due to a compensatory mechanism for the spinal coronal malalignment, correction of the spine may restore the pelvic coronal malalignment. If the spine is flexible, the shoe lift may yield a considerable amount of spinal coronal correction. However, if the spine is rigid, surgery is likely necessary, in conjunction with a shoe insert. Intraoperative full-cassette radiographs should be used to evaluate the coronal alignment and account for the patient's pelvic obliquity.

Global spinopelvic alignment relationships are becoming more important and are needed for a complete assessment of the patient's spinal deformity. It has been shown, as mentioned earlier, that the spinal regions are interrelated.^{3,5,11,16,48} A global approach is needed to correctly treat spinal deformity, despite where the actual pathology may be located within the spinal column. Lumbar spinal deformity may affect cervical alignment and vice versa. A marked LL (determined by PI) and TK will lead to a pronounced CL in order to maintain horizontal gaze. This has significant implications for patients with fixed alignment of the cervical spine (e.g. post-fusion) where modifications and compensation for malalignment in other regions of the spine cannot be taken on by the cervical region. Such considerations should also be taken into account in the setting of cervical disc arthroplasty, where the amount of cervical lordosis should be patient specific. Furthermore, cervical lordosis can be considered, similar to TK and LL, as an adaptive spinal segment to global alignment. When LL and TK are adapted to the patient's PI, cervical lordosis will be proportional to the other curves. In the setting of anterior malalignment (driven by a loss of LL and/or an increase in TK), cervical lordosis can be seen as a compensatory mechanism. This reciprocal change of cervical lordosis has been reported after realignment procedure for patients with significant anterior malalignment.^{50,51}

The SA of the cervical spine is becoming a very important parameter as the same concepts used to so successfully characterize the effect of thoracolumbar alignment on outcomes are applied to the cervical spine. Currently, there is only one study to date correlating cervical regional SA to HRQOL outcome scores.⁵² Tang et al.⁵² found that patients with increasing cervical SVA had poorer HRQOL scores and a cervical SVA > 4 cm is correlated to worse

health-related outcomes. These findings are the first step toward a comprehensive assessment of spinal malalignment and its effect on HRQOL. Furthermore, there is not a single agreed upon standard to measure cervical sagittal alignment.⁵³ Hardacker has suggested that the C2 plumb line could be used as a standard measure.⁵³ Future work will allow exploration and clarification into the exact relationship between the cervical spine and global sagittal alignment as well as their impact on HRQOL.

KEY POINTS

- Pelvic alignment including PI, PT, SS, and pelvic obliquity must be evaluated by the treating physicians in addition to more traditional measures such as SVA, LL, TK, and regional scoliotic curves. Failure to account for pelvic alignment when treating spinal deformity increases the risk of residual spinal deformity and treatment failure.
- Preoperative planning formulas that do not evaluate pelvic parameters, especially PI and PT, may be inaccurate, and increase the risk of postoperative malalignment; formulas that include PI, PT, LL, TK, and patient age are the most accurate.
- Pelvic obliquity and the associated etiology must be accounted for in strategies for coronal plane correction, as correction of lumbar curves in the setting of pelvic obliquity may generate postoperative coronal decompensation.
- The regional spinal segments are not independent of one another, and significant correlation of alignment exists from the pelvis to the cervical spine.
- When LL and TK are adapted to the patient's PI, cervical lordosis will be proportional to the other curves; however, in the case of anterior malalignment, cervical lordosis can be seen as a compensatory mechanism.

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Nonoperative Treatment of Adult Deformity

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Snapshot

- » Patient Education
- » Smoking
- » Morbid Obesity
- » Osteoporosis
- » Physical Therapy
- » Bracing
- » Chiropractic and Pilates Therapy
- » Pharmacologic Therapy
- » Injections
- » Others
- » Operative versus Nonoperative Treatment

INTRODUCTION

Adult spinal deformity encompasses a broad spectrum of pathology, including adult sequelae of persistent idiopathic scoliosis, “de novo” scoliosis secondary to age-related degenerative changes, sagittal plane deformity, post-traumatic or iatrogenic postsurgical deformity, and scoliosis secondary to metabolic bone disease (mostly osteoporosis). Adult degenerative scoliosis (ADS) or “de novo” scoliosis develops after skeletal maturity, with a coronal Cobb angle $>10^\circ$. It is secondary to asymmetric degenerative changes, without history of scoliosis in childhood or adolescence, and it typically presents in the sixth or seventh decade of life.^{1,2} Osteoporosis and micro/macro-vertebral compression fracture may contribute to overall degenerative process and development of ADS.² Adult degenerative scoliosis is rarely seen before the age of 40, in which case it likely represents progression of undiagnosed adolescent idiopathic scoliosis (AIS) that developed before skeletal maturity but became symptomatic later in adult life.^{1,2} Curves in ADS tend to be more rigid than in AIS and typically progress by 1–6° per year (average 3°).^{1,3} The prevalence of adult scoliosis among the elderly in a report from 2005 was 68%, which was higher than the previously reported prevalence of 32%.^{4,5} The report

from 2005 noted that, although many of the patients with adult scoliosis had pain and dysfunction, there was a large group that had no symptoms.⁴

Adults with scoliosis who are symptomatic characteristically present with pain and disability.^{2,6–8} This is often secondary to associated degenerative changes including degenerative disc disease, spinal and foraminal stenosis, facet arthropathy, spondylolisthesis, rotational subluxation, and rigidity within deformity.⁹ Therefore, clinical presentation is also variable and includes axial back pain, radiculopathy, neurogenic claudication, neurologic deficit, and progressive cosmetic deformity.^{8,10} Although radiographic features and cosmesis generally guide the treatment of AIS, the most important guiding principles for adult spinal deformity treatment are pain and disability.¹¹ Positive sagittal malalignment has the strongest correlation with pain and disability in ADS.^{12,13} Treatment of adult deformity is becoming an increasingly important part of spine practice due to the aging population and rising expectations for quality of life. Asymptomatic patients usually need no treatment, although periodic follow-up may be useful to assess for curve progression. In symptomatic adult scoliosis patients, although current literature suggests that surgery has the potential to offer significant improvement

in pain and disability compared to nonoperative treatment, nonoperative treatment should typically be the first-line treatment in the absence of significant and/or progressive neurologic deficit or rapidly progressive deformity.^{5,14,15}

Nonoperative treatments for adult deformity include physical therapy, chiropractic manipulation, pain management, injections, yoga, acupuncture, and medications. However, there are few reports in the literature focused on nonoperative treatment, and there is no consensus on nonsurgical treatment paradigms.^{6,16-18} In contrast, for lumbar degenerative disease without deformity, although there is lack of consensus on treatment paradigm, there is at least extensive literature addressing nonoperative treatment options.^{17,19-21} There are also several reports focused on nonsurgical treatment for adolescent spinal deformity, including bracing and exercise.^{17,22,23} However, there is a paucity of information on the nonoperative management of adult deformity.

Everett et al. in their systemic literature review of non-surgical treatment in adult scoliosis in 2007 found that evidence for nonoperative treatment of adult scoliosis was lacking based on a review of articles published from 1996 to 2007.¹⁶ There were only two articles on bracing that met the criteria of inclusion and only three articles were reviewed for physical therapy, of which one was a case series. There were two case series for chiropractic manipulation, and only one article focused on injections. These articles provided only weak Level IV evidence, except for the article on injections, which provided Level III evidence. The review of Everett et al. concluded that, although nonoperative treatment may appear to be a helpful option, there was significant lack of evidence in the literature to support it.¹⁶ Since this review, there have been a few notable additions to the literature regarding nonoperative treatment. Glassman et al. evaluated nonoperative treatment of adult spinal deformity in a series of articles addressing nonsurgical resource utilization, cost-benefit, and patient-based health outcome measures.^{6,17,18} There have also been efforts to develop predictive models based on clinical symptoms and radiographic parameters to determine which patients may be more likely to benefit from operative versus nonoperative treatment for the management of symptomatic adult spine deformity.^{5,6,8,14,15,24,25}

In an effort to study nonsurgical resource utilization in adult deformity, Glassman et al.¹⁷ in 2006 reviewed the enrollment data for 1,061 patients who entered into a prospective multicenter study for adult spinal deformity between January 2002 and June 2004. The mean age

was 48.2 years and enrollment criteria included: scoliosis $>30^\circ$, sagittal plane deformity with kyphosis $>60^\circ$, sagittal imbalance >6 cm, or history of scoliosis surgery >18 months before enrollment. Patients were enrolled in either a surgical arm ($n = 476$) or a nonsurgical arm ($n = 585$). Patients in the surgical arm were scheduled for surgery. Patients in the nonsurgical arm were divided into low-symptom and high-symptom subgroups based on an age-adjusted Oswestry Disability Index (ODI) score of less than or >20 . Patient-based health status measures, including Short Form-12 (SF-12), Scoliosis Research Society questionnaire-29 (SRS-29), and ODI were used for assessment. The operative and nonoperative groups were similar in terms of gender, curve type, and history of previous surgery. The high-symptom nonsurgical group was similar to the surgical group in terms of patient-related health outcome measures. One of the concerns regarding the study design was that adult deformity patients referred to a spine surgeon might be more symptomatic and may not represent the general adult deformity population, with the possibility of the majority of adult deformity patients being treated expectantly by primary care physicians and, therefore, leading to bias toward greater utilization of resources. This concern was offset to some extent by stratifying the nonsurgical patients into high- and low-symptom groups based on standardized health status measures and the finding that the low-symptom group was similar to the general population based on normalized SF-12 values. Resource utilization was assessed by recording the use of aerobic exercises, aquatic therapy, strength training, postural training, body mechanics physical training, analgesics, nonsteroidal anti-inflammatory drugs (NSAIDs), narcotics, pain management, epidural injections, facet or nerve blocks, bracing, and bed rest. The high-symptom group, which was more similar to the surgical group, was found to utilize significantly greater resources in general. The high-symptom group utilized pain management most (55%), followed by exercise and analgesics or NSAIDs (38% each). Notably, although the low-symptom nonsurgical group, which had similar standardized health measures as the general population, also had substantial resource utilization, with approximately 70% of these patients receiving nonoperative treatment related to their spinal deformity. The most frequently used treatments in the low-symptom group were exercise (33%), analgesics or NSAIDs (24%), and pain management (22%). Furthermore, of note was that, whereas the low-symptom group had more commonly not received any treatment prior

to enrollment, the high-symptom group had a significant history of previous resource utilization, including narcotics, epidural injections, exercise, and pain management referral, prior to enrollment in the study. Another finding was that the low-symptom group had a high percentage of adult patients with idiopathic scoliosis and the high-symptom group had a higher percentage of patients with sagittal plane deformity, which is consistent with the literature that sagittal plane deformity can have a particularly high impact on health-related quality of life (HRQOL). Patients in the low-symptoms group, once they enrolled in the study, were encouraged to increase use of the exercise method and decrease use of narcotics and pain management. In the high-symptoms group, there was an increase use of analgesics, pain management, and bed rest.

In a retrospective review of prospectively, consecutively enrolled patients ($n = 1,568$; 640 surgical and 940 nonsurgical), Glassman et al. in 2007 assessed selection criteria for operative versus nonoperative treatment of adult deformity patients.⁶ Case-control matching, which was one of the two analytical methods used, led to 161 surgical-nonsurgical pairs (322 patients) matched for further analysis. There were 247 patients for the logistic regression analysis, which was the second method of analysis. They stratified the parameters that influenced surgical decision for the surgeons and patients into groups, including preoperative factors, radiographic measures, clinical symptoms, functional limitations, and appearance, or social issues. They found that preoperative risk factors, including higher body mass index (BMI), history of cardiac disease, and a poor General Health SF-12 subscale score differed significantly between the surgical and nonsurgical groups. Nonsurgical patients had greater preoperative risk factors. Based on logistic regression analysis, younger patients were more likely to be treated surgically. The only radiographic parameters associated with increased likelihood of surgical treatment were greater thoracic and thoracolumbar/lumbar Cobb angles and great thoracolumbar/lumbar apical vertebral translation. Multiple studies have shown that thoracolumbar curves are associated with greater severity of symptoms compared with thoracic curves, but there was no correlation between curve magnitude and degree of pain.^{12,26} An interesting finding was the lack of strong correlation between positive sagittal balance and surgical treatment, although sagittal imbalance has been shown to have a particularly strong correlation with pain and disability in ADS and restoration

of sagittal alignment remains a high priority in spinal deformity surgery.^{12,13,26,27} This may be because patients with sagittal imbalance may have been excluded because their primary diagnosis was not adult idiopathic scoliosis (one of the inclusion criteria of the study). It is also possible that the propensity score may have inadvertently matched the surgical and nonsurgical groups for sagittal balance. The surgical patients had more frequent leg pain (47% vs. 35%), greater mean level of daily back pain, and more frequent moderate-to-severe back pain in the last 6 months. One of the interesting findings of the study was that the patient's perception of appearance and social function influenced their decision to pursue surgical treatment.

In another study in 2010, Glassman et al. studied the costs and benefits of nonoperative management for adult scoliosis.¹⁸ A total of 123 patients with a mean age of 53.3 years (range: (18–79 years) was evaluated. Patients were segregated based on their pretreatment ODI into a low-symptom group ($ODI \leq 20$), mid-symptom group ($ODI = 21-40$) or high-symptom group ($ODI \geq 40$). Nonoperative treatment included medication, exercise therapy, modality physical therapy, chiropractic treatment, pain management referrals, and injections. Among the 68 adult scoliosis patients who received nonoperative treatment, there was no significant change in any of the HRQOL outcome parameters over 2 years. This trend was also observed in the stratified groups based on pretreatment severity. The mean nonoperative treatment cost over the 2-year period was \$10,815, with an average cost of \$9,704 for patients in the low-symptom group, \$11,116 for patients in the mid-symptom group, and \$14,022 for patients in the high-symptom group. This study had limitations, including that the study population consisted of patients referred to a tertiary spine center for the evaluation of their scoliosis and, therefore, may not represent the general population of adult scoliosis patients. Another issue was that the study was not well delineated in terms of indication or specific technique, which raised the possibility that a subgroup of patients may benefit from a clearly defined nonoperative regimen and a possibility that some of the patients may have deteriorated if they did not have the benefit of nonoperative treatments.

PATIENT EDUCATION

Including the patient in discussing the potential causes of pain and the disease process is important in the management of adult deformity. This gives the physician an

opportunity to understand the symptoms better and, at the same time, helps patients better understand the potential reasons for their pain, in turn making them more active participants in their treatment plan. This also provides the opportunity to discuss risk factors and life style modifications, such as smoking cessation, weight loss in obese patients, and treatment of osteoporosis. It is also important to address these factors while the patient is undergoing nonoperative treatment, because they may complicate surgical intervention, if needed, in the future. This discussion also provides the opportunity to assess patient motivation and commitment to work toward the goals of eliminating or reducing the risk factors and achieving better functional lifestyle, which may be important guiding factors for any future surgical intervention. Possible therapies should be recommended after considering and discussing the natural history of adult spine deformity, history of previously received therapy, and risk and benefits of operative and nonoperative treatment. Although current literature suggests that surgical intervention may offer better outcomes with regard to pain and disability in adult deformity patients, nonoperative treatment should typically be the first line of therapy for most adult deformity patients.^{5,6,15}

Factors that may lead to transition from nonoperative treatment to operative treatment are not fully understood. Failure of conservative treatment, severe radiculopathy, neurologic deficit, and positive sagittal malalignment have been associated with this transition.^{6,8,24} Several factors should be considered before making the transition toward surgical intervention, including severity of symptoms, functionality and quality of life, health of the patient, and the patient's understanding of and willingness to accept the risks of surgery.⁵ There should be a clear discussion with patients regarding potential risks and benefits associated with different treatment options, especially for surgical interventions, such that both the patient and surgeon have similar expectations.²⁴ It is also important to recognize that although operative treatment of symptomatic adult deformity may offer the potential for better outcomes, these assessment are based on averages across large groups of patients and not all patients will have similar outcomes. The outcomes vary from significant improvement to unchanged or worsening of symptoms in some cases.²⁵

SMOKING

Cigarette smoking has a known association with increased risk of back pain and degenerative disc disease.^{28,29} Moreover, the adverse impact of cigarette smoking on spinal

fusion is well known.^{30,31} Nearly 19% of Americans continue to smoke, despite smoking rates declining.³² Nicotine is an established cause for the addictive component and adverse effects of smoking.³³ It causes reduced blood supply, tissue hypoxia, and affects arteriole endothelial receptors leading to reduced bone metabolic activity.^{34,35} It also causes selective depletion of bone marrow β -lymphocytes and decreased calcium absorption, and interferes with osteoblastic function, all of which may be contributing factor for decreased bone formation.^{36,37} Elevated levels of proinflammatory mediators in smokers may amplify pain.³⁸ A recent meta-analysis of 40 studies showed that smoking was associated with increased prevalence of low back pain and increased risk of having chronic back pain or disabling back pain.²⁸ Smoking may also exacerbate postmenopausal and aging-related bone loss. Postmenopausal women who smoke are more prone to vertebral fractures and low vertebral bone mineral density.³³

Glassman et al. retrospectively studied the effects of cigarette smoking and smoking cessation on spinal fusion.³⁰ The nonunion rate was 14.2% for nonsmokers versus 26.5% in patients who continued to smoke after surgery. For patients who quit smoking <6 months, the nonunion rate was 17.1%, which was slightly better than the 18.2% in patients who quit for 1–6 months after surgery. Both rates were better than in smokers (26.5%) but higher in comparison to nonsmokers (14.2%). Successful postoperative smoking cessation was related to the amount of smoking before surgery and ability to quit smoking preoperatively, but improved outcomes were related to postoperative rather than preoperative smoking cessation. Analysis of return-to-work data showed that patients who quit smoking for > 6 months postoperatively were more likely to go back to full or light duty work (74.6%) than nonquitters (53.6%).³⁰

The most common perioperative complications attributed to smoking are wound-healing, infection, and cardiopulmonary complications.^{33,39,40} Although there are no definite guidelines for smoking cessation, it has been shown that longer periods of smoking cessation decrease the incidence of postoperative complication.^{33,39–41} Smokers should be encouraged and counseled to quit smoking as it has been shown to have an association with degenerative disc disease and back pain. Patients should be informed that smoking also has adverse effects on spine fusion, in the event that their deformity warrants it and they wish to pursue surgery in the future. Patients should be encour-

aged to discuss smoking cessation with their primary care physician, as smoking interventions such as counseling and pharmacotherapy have shown to increase the chances of abstinence.⁴² Nicotine is primarily metabolized in liver, and its metabolite cotinine is used to screen recent smoking. It has a half-life of 14–20 hours and can be detected in urine for approximately 10 days after cessation.³³

MORBID OBESITY

Obesity is a major health problem in the United States and has reached epidemic proportion. Overweight is defined as a BMI of 25.0–29.9, and a BMI of >30.0 is considered to be obesity.⁴³ The World Health Organization grades obesity as grade 1 (BMI 30–34.9), grade 2 (BMI 35–39.9), and grade 3 or morbid obesity (BMI ≥ 40).⁴⁴ The prevalence of obesity in the United States is high and, except for men aged 20–29 years, it is over 30%. Flegal et al. reported the prevalence of obesity to be 32.2% in adult men and 35.5% in adult women.⁴⁵ These proportions continue to rise although, in the last decade, the rate has slowed down especially for women and possibly for men in comparison to the previous decade.⁴⁵ Obesity has been shown to be associated with multiple health problems including diabetes, hypertension, high cholesterol, stroke, heart disease, certain cancers, and arthritis. Higher grades of obesity have been associated with excess mortality, particularly from cardiovascular disease, diabetes, and obesity-related cancers.^{46,47} Obesity has also been shown to be an independent risk factor for low back pain and degenerative spine disease, especially of the lumbar spine.^{48,49}

With regard to spine surgery, there are only limited studies investigating the effect of obesity on spine surgery outcomes. Many studies have found that there is no difference between the clinical outcomes for back surgery for proper indications.^{50–52} Initial studies did not include patient-directed quality of life measures, but Djurasovic et al. in their study included the Short Form-36 (SF-36), General Health Instrument, and ODI in assessing patient outcomes.⁵¹ They concluded that obese patients with proper indications for surgery achieve similar benefits and improvement with lumbar fusion as nonobese patients. Morbid obesity has also been associated with higher hospital costs and higher complication rates, with wound infection being the most common complication followed by pulmonary complications.^{51,53,54} Djurasovic et al., in their study, found a statistically significant increase in wound-related complications in obese patients (5.5%).⁵¹

There have been few studies evaluating the effect of obesity on scoliosis surgery and most of them are for

idiopathic scoliosis surgery. Upasani et al. in 2008 in a multicenter retrospective review of 241 patients examined the effect of BMI on surgical outcomes.⁵² Although obese patients (BMI ≥ 35) had increased preoperative kyphosis, it did not affect the surgical goal of achieving similar correction of the deformity. Another study analyzing proximal junctional kyphosis (PJK) in primary adult deformity surgery found that a PJK $\geq 20^\circ$ in primary adult idiopathic/degenerative scoliosis was associated with older age, shorter constructs starting in the lower thoracic spine, obesity, and fusion to the sacrum.⁵⁵ Although a recent report suggests that obesity is not related to increased risk of morbidity in anterior lumbar surgery, obese patients have significantly longer duration of anterior exposure, longer duration of the anterior surgery, longer length of anterior incision, and more depth from skin to fascia and from fascia to spine compared with nonobese patients.⁵⁶

Although obesity itself is not necessarily a contradiction for surgical intervention, if indicated in the obese patient, the importance of weight loss should be discussed with patients in the context of overall health and beneficial effects for the spine and postoperative rehabilitation. In morbidly obese patients with significant comorbidities, consultation with bariatric surgery can be an option to consider. Addressing obesity as part of a nonoperative treatment approach may reduce load on the spine and improve symptoms in addition to helping improve the ability of the patient to tolerate surgical treatment should this be warranted and pursued in the future.

OSTEOPOROSIS

Osteoporosis/osteopenia may play a role in adult spine deformity and its progression, but it has been suggested that there is not a significant role for osteoporosis/osteopenia in the progression of ADS curve.^{57,58} It has been shown that postmenopausal bone loss is similar in both adult scoliosis patients and the general population.⁵⁸ However, fractures secondary to osteoporosis may cause an asymmetric configuration, which may lead to kyphosis or scoliosis or both and may occur in preexisting scoliosis.²

Elderly patients should get work up for osteoporosis including dual-energy X-ray absorptiometry and be treated accordingly. Notably, it has been suggested that degenerative scoliosis may cause false elevation of spinal bone mineral density.⁵⁹

PHYSICAL THERAPY

There is Level IV, weak evidence for the use of physical therapy as a part of nonoperative treatment of adult

deformity.¹⁶ In a clinical study of approximately 30 patients with degenerative scoliosis, patients underwent an FED (fixation, elongation, and de-rotation) type of physical therapy. The patients were initially treated with heat, followed by three-dimensional fixation in an FED unit, with elongation and de-rotation through traction and corrective pressures.⁶⁰ It was performed intermittently or continuously with periods of relaxation. Patients received 60 cycles of therapy. Patients were treated with NSAIDs as needed for pain. The authors found a statistically significant improvement of pain and curve improvement.⁶⁰ However, the study had significant limitations, since the traction protocol, number of patients by degree of curve magnitude, and the independence of radiograph reviewers were not described in the study, making the study conclusions difficult to corroborate.¹⁶

In another study of 69 skeletally mature patients, specific side-shift exercises did not show any significant improvement of symptoms.^{16,61} In another study, 8 weeks of aquatic therapy decreased levels of back pain and disability, increased quality of life, and improved health-related fitness in adults with chronic low back pain. A dose-dependent response effect was observed in some parameters, with greater benefits with 3 days of exercise per week compared with 2 days of exercise per week.⁶²

BRACING

Thoracolumbosacral orthotics and lumbosacral orthotics have no significant role in the nonoperative management of adult spinal deformity.^{16,63} Although these braces may provide short-term pain control, long-term use may lead to muscle deconditioning. In addition, bracing does not have a significant effect on curve progression, as it is not secondary to spinal growth in this population.^{1,16,63,64}

CHIROPRACTIC AND PILATES THERAPY

The best evidence for chiropractic manipulation is very weak and Level IV case studies.¹⁶ In those studies, it was found to be helpful for temporary pain relief and possible to slow curve progression.^{65,66} In one of the case studies, it was found that the addition of Pilates to chiropractic care improved pain relief, and the authors reported that the sacro-occipital technique is an effective chiropractic maneuver in scoliosis.⁶⁵

PHARMACOLOGIC THERAPY

Pharmacologic agents such as NSAIDs, narcotic analgesics, muscle relaxers, and anticonvulsants have been used

to treat spinal pain. There is no specific literature for adult spinal deformity patients, but there are data regarding their use in spinal pain.

There is good evidence for the efficacy of NSAIDs for acute back pain, but the evidence is less convincing for chronic back pain.⁶⁷⁻⁷⁰ There is no clear evidence that opioid analgesics are more effective than NSAIDs.^{67,69} No single type of NSAID appears to be more effective than the others.^{67,69} Patients and physicians should be aware of the common gastrointestinal and renal toxicity associated with NSAIDs. Nonsteroidal anti-inflammatory drug-induced acute renal failure is second only to aminoglycoside-induced renal failure and accounts for 15% of all drug-induced renal failure.^{68,71} It occurs usually secondary to prostaglandin inhibition and is often, but not always, reversible. Gastrointestinal toxicity occurs in approximately 1-2% of NSAID users.^{68,72} There is also concern of cardiovascular complications.^{68,73} Often, NSAIDs are first-line treatments of spinal pain. Although there is only limited evidence regarding acetaminophen use in comparison to NSAIDs, it may also be used for mild back pain, especially among patients who cannot tolerate NSAIDs.⁶⁷

Tramadol exhibits weak opioid effects and inhibits serotonin and norepinephrine reuptake. It has been shown to be effective for short-term improvement of pain and function in the treatment of low back pain, but there are no good data regarding long-term use.^{69,74} Major side effects include dizziness, nausea, sedation, constipation, and headache. In addition, its use above the recommended dose is associated with seizures.⁶⁸

Opioids can be used in the treatment of chronic spine pain, but should be avoided if possible. There is no good evidence that opioids are more effective than NSAIDs.⁷⁰ There is only one trial that compared opioids with other analgesics, which was naproxen.^{69,74} Although it had greater pain relief, it did not lead to greater improvement of patient activity. Opioids have a potentially greater risk of side effects, decreasing effectiveness related to habituation when used long term, and have a high potential for addiction.⁶⁸⁻⁷⁰ A comparison of patients treated with narcotic versus non-narcotic medication over 2 years showed no significant difference in HRQOL.¹⁸

Muscle relaxers have been reported to be moderately superior to placebo for short-term pain relief, but are less effective than NSAIDs and were associated with more side effects.⁷⁵ The side effects are often central nervous system related, and mainly include sedation and dizziness. Anticonvulsant medications including gabapentin

and carbamazepine have been shown to have some effect on radiculopathy. There are limited studies showing modest improvements in pain scores when compared with placebo.⁶⁹ Side effects for gabapentin include drowsiness, loss of energy, and dizziness.⁶⁹ Pregabalin works in a similar way and has been reported to have some benefit, but the data are limited.⁶⁸ Antidepressants have also been used for chronic back pain and there is some evidence that these are more effective than placebo for pain relief, but there is no evidence of clear benefit of functional outcomes.^{68,69}

INJECTIONS

Interventional pain management is an emerging subspecialty in the management of spine pain. There is limited literature regarding the role of injections for adult spine deformity-related pain as shown in the systemic review by Everett et al. in which they could only find one article for epidural injections that met the criteria for the study.¹⁶ This was a retrospective study of 61 patients with degenerative scoliosis (coronal Cobb angle $> 10^\circ$) and radicular complaints by Cooper et al. that explored the role of fluoroscopic transforaminal epidural steroid injection (ESI) for the radicular pain. They found these injections to be effective treatment options for patients with degenerative lumbar scoliotic stenosis and radiculopathy.⁷⁶ In their study, successful outcomes were reported in approximately 60% of patients at 1 week following injection, 56% at 1 month following injection, 37% at 1 year following injection, and 27% at 2 years following injection. Although there are very limited data for the role of ESI for adult spine deformity-related pain, it is the strongest (Level III) among the different nonoperative treatment modalities, as there is only Level IV evidence for other nonoperative treatment modalities for adult spine deformity.¹⁶

There is growing evidence for the role of interventional pain management for pain from degenerative spine disease, but more so for short-term relief than long-term relief. Pain in adult spine deformity is multifactorial and may be secondary to muscle fatigue and spasm, spinal imbalance, facet arthropathy, degenerative disc disease, foraminal and central canal stenosis, and spondylolisthesis.^{2,10,77} Therefore, interventional pain management procedures, including facet joint injections, epidural injections, selective transforaminal nerve block, trigger point injections, and sacroiliac joint injections, may be helpful for pain management in some adults with spinal deformity. Many of the causes of the spinal pain in adult deformity

patients are acute recurrent problems that are characterized by periods of quiescence with episodic flare-ups, and injections could be particularly helpful in these patients in temporarily easing symptoms during the episodes of flare-up.

Epidural injections, selective nerve root blocks, and facet injections may be effective for both therapeutic and diagnostic purposes.^{78,79} These can be diagnostic by helping to localize the cause of pain, if there is question regarding its source. There is better evidence for the role of ESI in disc herniation/lumbar radiculitis than spinal stenosis, and no clear evidence for axial or discogenic back pain, and the therapeutic benefit is better in short-term than the long-term.^{78,79} Most studies show no difference in surgical rates between patients treated with ESI and control patients; however, some randomized studies conducted by spine surgeons showed, in some patients, that the strategic use of ESI may help to prevent or delay the need for surgery.^{80,81}

The American Society of Intervention Pain Physicians in 2013 published the revised guidelines for interventional pain management.⁷⁸ For epidural injections (caudal, interlaminar, and transforaminal) in the diagnostic phase, a patient may receive two procedures at intervals of no sooner than 2 weeks or, preferably, 4 weeks. In the therapeutic phase, the recommended frequency of interventional techniques should be ≥ 2 months between each injection, provided that $> 50\%$ relief is obtained for 2 months. If neural blockade is applied to different regions, the guidelines recommend performing these at intervals of no sooner than 1 week and preferably 2 weeks for most types of procedures, and the therapeutic frequency may remain at intervals of at least 2 months for each region. However, the guidelines suggest that all regions can be treated at the same time, if all procedures can be performed safely. Cervical and thoracic regions are considered as one region; lumbar and sacral are considered as one region. Epidural injections should be repeated only as medically necessary, and are recommended to be limited to a maximum of 4 times per year.⁷⁸ For facet blocks, the recommendation is similar for both diagnostic and therapeutic purposes, with suggested frequency of 2- to 3-month intervals between injections, provided that $> 50\%$ relief is obtained for 2 months, with a maximum of 4 times for local anesthetic and steroid blocks over a period of 1 year per region. Under unusual circumstances, with a recurrent injury or cervicogenic headache, procedures may be repeated 6 times in a year after stabilization in the treatment phase.⁷⁸ The recommendations for

sacroiliac joint injections are similar, provided that there is > 50% relief in symptoms for at least 6 weeks.⁷⁸

OTHERS

Other nontraditional treatment modalities like *Yoga*, massage therapy, acupuncture,⁸² transcutaneous electrical nerve stimulation, and percutaneous electrical nerve stimulation may be tried and pursued if the patient perceives benefit, but presently, there is no clear evidence to support these approaches.

OPERATIVE VERSUS NONOPERATIVE TREATMENT

Multiple studies have shown long-term benefit with surgical treatment of adult deformity.^{5,8,14,15,24,25} This contrasts with the lack of good-quality data to support nonoperative treatment.^{6,16,18} Smith et al., in their recent studies, evaluated the role of surgical treatment in adult spinal deformity with regard to leg pain and back pain in two separate studies.^{14,15} In the first study analyzing improvement of back pain with operative and nonoperative treatment in adults with scoliosis, Smith et al. found that, despite starting with significantly greater back pain and disability and worse health status, surgically treated patients had significantly better outcome at the 2-year follow-up compared with patients treated nonoperatively.¹⁵ Of 317 patients with back pain, 147 (46%) were managed surgically and 170 (54%) were managed nonsurgically. Compared with nonsurgical patients, surgical patients had higher base line mean numeric rating score (NRS) for back pain (6.3 vs. 4.8; $P < 0.001$), higher mean ODI score (35 vs. 24; $P < 0.001$), and lower mean SRS-22 scores (3.1 vs. 3.4; $P < 0.001$). At the 2 years follow-up nonsurgical patients did not have significant change in NRS score for back pain ($P = 0.9$), ODI ($P = 0.7$), or SRS-22 ($P = 0.9$), whereas surgically treated patients had significant improvement in all three parameters, with NRS score of 6.3–2.6 ($P < 0.001$), ODI of 35–20 ($P < 0.001$), and SRS-22 of 3.1–3.8 ($P < 0.001$). Furthermore, compared to nonsurgical patients, at the time of the 2-year follow-up, surgically treated patients had better NRS, ODI, and SRS-22 scores.¹⁵

Similarly, in the second study that analyzed leg pain in adult deformity patients based on a retrospective review of prospectively collected data with 2-year follow-up, Smith et al. concluded that there was significant improvement in mean NRS score for leg pain and ODI in

surgically treated patients. Nonsurgically treated patients showed no significant improvement at the 2-year follow-up.¹⁴

In deciding between an operative and nonoperative treatment approach, it should be recognized that surgery has significant associated risks with reported complication rates ranging from 10% to 96%.²⁴ In assessing the risks versus benefits of surgery for adult scoliosis, Smith et al. reported a strong association between complication rates and patient age.⁵ The total complication rates for the age groups of 25–44, 45–64, and 65–85 years were 17%, 42%, and 71% respectively, including major complication rates of 6%, 15%, and 29%, respectively.⁵ The older patients had a significantly greater degree of pain, disability, and worse health status at baseline. Patients in all age groups showed significant improvement in disability at 2-year follow-up, with ODI showing significantly greater improvement in older patients. Despite high complication rates in the older age group, at the 2-year follow-up, the health outcome measures were indistinguishable from other groups, suggesting that, despite having greater risk of complications from adult deformity surgery, the elderly group also had a better chance of greater improvement in disability and pain compared to younger patients.⁵

CONCLUSION

There are high- and low-symptom groups among adult deformity patients, and both groups appear to utilize nonsurgical resources. Although evidence is still lacking, conservative treatment is a valuable option in the treatment of adult deformity. The objective of nonoperative treatment is relief from pain and improvement in the functional capacity of the patient, and a trial of conservative treatment should be done before considering surgical treatment in most adult deformity patients. Some patients with severe disabling pain, who may have already exhausted all conservative modalities before seeing a spine surgeon or patients with severe radiculopathy symptoms, neurogenic claudication, or neurologic deficit, may be candidates for operative treatment without trying further conservative treatment. When deciding between operative versus nonoperative treatment approaches, several factors should be considered, including severity of symptoms, quality of life, overall health of the patient, and understanding and willingness of the patient to accept the risks associated with surgery. The current literature has several reasonable quality studies that provide risk and benefit

assessment of operative treatment of adult spine deformity, but there is still a paucity of literature regarding nonoperative treatments. More clinical research is needed to clarify the optimal nonoperative treatment paradigm.

KEY POINTS

- There is a lack of high-quality data for nonoperative treatment options for adult spinal deformity.
- There is significant utilization of nonoperative treatment resources by adult deformity patients.
- No lasting improvement in HRQOL has been reported in adult spinal deformity patients undergoing nonoperative treatment when compared to untreated patients.
- Prospective studies designed to specify indications and guidelines for nonoperative treatment are needed.

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Preoperative Considerations for the Adult Deformity Patient

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Snapshot

- » Imaging
- » Cardiac
- » Pulmonary
- » Communication/Psychiatric/Social Issues
- » Nutrition
- » Bone Mineral Density
- » Pain Management
- » Infection

INTRODUCTION

Spine surgery for the management of adult deformity has increased significantly over the past two decades. It is well recognized that adult spinal deformity has a higher rate of complications than other types of spine surgery. Surgical procedures for adult deformity often include long segment fusions, anterior/posterior combined procedures, and surgery that is being revised from earlier procedures—all of this increases the physiologic toll that accompanies the surgery. The purpose of this chapter is to review the process of preoperative preparation of adults for spinal deformity surgery.

Spinal deformity surgery in the adult presents challenges to the spine surgeon in many different fashions. These surgeries are often larger in scope than most adult spinal surgeries and present a set of complications that is somewhat expanded compared to spinal surgery done on a smaller scale. Awareness of the potential complications allows the spinal surgeon to lessen the chance that they will occur. This requires a focus not just on the technical aspects of the surgical procedure, but on the overall medical condition of the patient. Often, complications are seen in other organ systems after adult spinal deformity surgery—this necessitates a multidisciplinary approach to these patients often starting prior to the surgical

procedure. The consultants from various fields can play a role preoperatively in identification of potential problems and maximization of the patient's health status prior to surgery. Much of the information in this chapter is drawn from the literature of respective fields of medicine. Older adults in the United States are increasing physically active into their older years and wish to remain so. The aging population also, however, accumulates comorbidities. These comorbidities play an important role in the stratification of risk perioperatively. Up to 68% of the population older than 60 has some form of spinal deformity, which can result in the limitation of activity.¹ The goals of deformity surgery in broad terms are to restore sagittal alignment and to decompress stenosis. The goal of this chapter is to draw attention to conditions that potentially can affect perioperative complications and patient outcomes. These conditions may be modifiable in some cases. In the event that they are, they generally should be optimized prior to surgery. Attention to and optimization of medical conditions allow complex surgery to be performed on this elderly population, who have been found to benefit substantially from deformity correction.² The cardiac, pulmonary, psychiatric, and nutritional systems can all potentially be optimized prior to surgery. In addition, this is often an aging population and the evaluation of bone mineral density (BMD) becomes important. Also, areas such as patient

communication cannot be overlooked in this process. Each of these areas will be expanded upon in the following pages. The single most important tool in the preparation of the patient for adult spinal deformity surgery is the history and physical examination as this will be the window into each patient's unique set of risks for surgery. The history should pay special attention for any possible bleeding or thrombotic disorders—these may be related to genetic syndromes, supplement induced or related to medication that is taken for a variety of diseases.

Many adult deformity patients require extensive front back surgery from multiple approaches. The timing of these separate stages becomes important in regard to possible complications. Passias et al. compared the complication rate of front-back procedures done on the same day versus those done in a staged fashion and found a statistically significant difference favoring doing the front-back procedure in one day.³ Hassanzadeh et al. looked the timing of surgical staging and found that in patients who require both anterior and posterior surgery, staging the two procedure 21 or more days apart decreases total perioperative transfusion requirements, although significantly improving their functional outcomes versus staging the procedure by a shorter time interval.⁴

IMAGING

Depending on the practice environment in which you are working, many of your patients may present with magnetic resonance imaging (MRI) obtained prior to consultation. Because of the degenerative nature of the majority of adult spinal deformity, it is recommended to obtain and review a recent MRI in the preoperative workup. This is due to the fact that these patients have a high rate of concomitant conditions such as diffuse degenerative changes resulting in stenosis that may warrant decompression at the time of the surgical intervention aimed at the deformity. In patients who have had prior surgery with instrumentation, the MRI may be affected by metal artifact to the point of rendering it ineffective at visualization of the space available for the neural elements. The rates of repeat revision for adult spinal deformity were reported by Kelly et al. as a 21% (most commonly this was due to pseudoarthrosis, adjacent segment disease, infection and implant prominence/pain).⁵ In this setting, computed tomography myelography would likely be a better choice of the instrumented area of the spine. This allows one to take a critical look at the position of the existing instrumentation and

assess for signs of malposition, failure, or loosening. Other conditions such as the presence of magnetically activated implanted devices (pacemakers, insulin pumps, neurostimulators, cochlear implants) or metal in the brain or the eye may serve as other contraindications to MRI.

CARDIAC

Cardiac conditions are often exacerbated in the perioperative period. Avoidance of these complications can be particularly fruitful as cardiac complications have been found to be harbingers of other complications—meaning that those suffering a cardiac complication were found to be more likely to have another complication.⁶ The preoperative screening electrocardiogram (EKG) is a commonly ordered part of the workup around the time of surgery. The somewhat controversial part is whether to order an EKG in a patient without any documented or risk factors for coronary artery disease (CAD) before noncardiac surgery. The Task Force of the American Society of Anesthesiologists Practice Advisory on Preanesthesia Evaluation incorporates the integration of patient history and the surgical procedure into the decision to perform this basic test.⁷ The Task Force recognized that age alone may not be an indication for an EKG, but that there is not enough evidence to make a more definitive recommendation. The EKG is indicated without question in the setting of known cardiovascular disease or identified risk factors. Depending on the extent of the cardiac history and also on the findings of the EKG, further cardiac workup may be recommended. This generally means either a stress test, an imaging procedure such as a radionuclide scan or echocardiogram, or a cardiac catheterization. The direction of this testing would be under the supervision of the cardiologist or the anesthesiologist. If an EKG is obtained in a patient without document risk, then that information would rarely, if ever lead to decision to perform coronary revascularization. However, it may lead to the initiation or alteration of medical therapy for patients with occult disease.⁸ It is worth pointing out that any significant findings should be fully investigated and possibly addressed prior to elective surgery.

Many patients will not have a specific pathology that is amenable to procedural intervention, but they may benefit from perioperative beta-blocker therapy. The majority of ischemic complications take place the first week after surgery and are thought to be a result of an exaggerated sympathetic response that occurs perioperatively.⁹ Initiation of beta-blocker therapy should be considered in

patients who have both significant risk factors such as cerebrovascular disease, diabetes requiring insulin, chronic renal insufficiency, and CAD; and also for patients with two or more of the following: hypertension, elevated low-density lipoprotein cholesterol >240, positive smoking status, >64 years old, and diabetes not requiring insulin.^{10,11} The largest trial to evaluate the use of beta-blockers for reduction in cardiac complications is the POISE trial.¹² They looked at over 8,000 patients with CAD or at risk of CAD and assigned them to extended release metoprolol versus placebo. They found that the metoprolol group had a lower rate of myocardial infarction; however, significantly more deaths occurred in this group due to a higher incidence of stroke. The flaw in the trial was the use of extended release metoprolol, which cannot be titrated to heart rate given its long half-life. After that trial, the American College of Cardiology and the American Heart Association recommended beta-blocker therapy titrated to heart rate and blood pressure.¹³ The evidence as it relates to orthopedics specifically is not large. Urban et al. looked at 107 patients with ischemic heart disease undergoing elective total knee arthroplasty.¹⁴ They were randomized to either an esmolol drip titrated to a HR <80, then transferred over to oral metoprolol versus physician directed hemodynamic control. The incidence of myocardial ischemia was not significantly different; though there was more ischemic time in the control group.

The fact that there is a good chance that the patient will need a blood transfusion either intraoperatively or in the perioperative period should be discussed ahead of time as some patients have religious or other objections to receiving blood. In certain instances, this may preclude them from surgery.

PULMONARY

Pulmonary complications are not uncommon in the perioperative period and include entities such as atelectasis, bronchospasm, pneumonia, prolonged mechanical ventilation, exacerbation of underlying pulmonary disease, and respiratory failure. The factors that are primarily correlated with increased risk are patient age, general health status, and chronic obstructive pulmonary disease (COPD).¹⁵ These should be considered during the preoperative evaluation. In regard to “general health status,” this is evaluated preoperatively by the anesthesiologist using the American Society of Anesthesiologists (ASA) physical status classification. The ASA was created to correlate with

overall mortality risk, but it has been shown to predict pulmonary and cardiovascular complications as well.¹⁶

ASA Classification

ASA I	Normal healthy patients
ASA II	Patients with mild systemic disease
ASA III	Patients with severe systemic disease that is limiting but not incapacitating
ASA IV	Patients with incapacitating disease which is a constant threat to life
ASA V	Moribund patients not expected to live more than 24 hours
ASA VI	A declared brain-dead patient whose organs are being removed for donor purposes

The chest X-Ray is routinely obtained as part of the preoperative workup. There does not appear to be evidence to support routine ordering of a chest radiograph in a patient without history based on physical examination findings relating to pathology of the chest. Routine chest radiography may result in more misleading than helpful results.¹⁷ The abandonment of routine use of chest radiography was examined in a group of 3866 patients, of which 28% had chest X-rays ordered preoperatively based on an institutional protocol. Of the rest, there was no complication that could be linked to lack of a chest X-ray.¹⁸ In patients with documented lung disease, a chest radiograph is indicated and further workup may be needed. It should be noted that both COPD and bronchial asthma are risk factors for osteoporosis; these patients are often treated with inhaled or oral steroids, which can contribute to bone loss. Associations between pulmonary disease and decreased BMD have been documented in the literature.^{19,20} A study conducted on a healthy population, however, found no association between lung function and bone mass after adjusting for body size and other confounders.²¹ The presence of COPD is associated with an increase in pulmonary complications in the setting of any surgical procedure.¹⁵ The other common preoperative pulmonary question relates to whether pulmonary function testing (PFT) is needed. It appears that unless the patient is undergoing a lung resection—then PFTs have not been shown to predict risk more accurately than clinical evaluation.²² It is notable that these tests are often ordered in the pediatric scoliosis patient, though this is often an academic exercise. Weinstein et al. did show a correlation between right thoracic curve magnitude and decreased pulmonary function, though this is not generally clinically relevant until the curve reaches 100°. ²³ In the adult

population, there is a greater incidence of comorbidities that may indicate the ordering of PFTs, but it generally is not the scoliosis itself.

The role of smoking as a general health risk is well known and extensively documented. It may be the greatest modifiable risk factor that we face. There are numerous studies that have linked smoking specifically to deleterious findings of various sorts in spine surgery. The American College of Surgeons National Surgical Quality Improvement database looked at 14,500 adults undergoing spine surgery and divided them into active, prior, or never smokers.²⁴ The prior smokers were significantly more likely to have prolonged hospitalization compared with the never smokers. Active smokers with >60 pack years were more likely to die within 30 days of surgery. Perhaps most concerning is the association between smoking and the inhibition of lumbar spinal fusion.²⁵ Silcox et al. in an animal model established a direct link between nonunion and the presence of systemic nicotine, and found that the bone that formed when nicotine was present was biomechanically inferior.²⁵ Smoking has been documented as an indicator of unfavorable outcomes in lumbar fusion for chronic low back pain patients, a predictor of poorer outcomes in lumbar spinal stenosis patients, and a predictor of inferior results after lumbar discectomy.²⁶⁻²⁸ Smoking has been documented as a risk factor for the development of pneumonia in the postoperative period in a variety of surgical cases.²⁹ Encouragingly, Glassman et al. showed that postoperative smoking cessation helps to reverse the impact of cigarette smoking on outcomes after spinal fusion.³⁰ They found nonunion rates of 14%, 17% and 27%, respectively, for nonsmoking, those who quit for longer than 6 months after surgery, and for those that continued to smoke. Because of these factors, most surgeons will require that a patient stop smoking and discontinue the use of other forms of tobacco prior to surgery.

In the postoperative period, the most important strategies for pulmonary function optimization are lung expansion and pain management. A meta-analysis of 14 randomized controlled trials of lung expansion maneuvers found that incentive spirometry and deep breathing exercises each reduced the risk of postoperative pulmonary complications by about 50%.³¹ Continuous positive airway pressure is also an effective strategy in patients who cannot cooperate with effort-dependent modalities.³¹

The most feared perioperative pulmonary condition is likely the development of pulmonary embolic disease. In a patient who would be considered high risk for deep

vein thrombosis (DVT) or pulmonary embolism (PE) in the perioperative period, consideration should be given to the placement of an inferior vena cava (IVC) filter preoperatively. There does not appear to be any level I evidence regarding the use of chemoprophylaxis in spine surgery. McClendon et al. looked at patients that they considered high risk (criteria included a history of DVT/PE, hypercoagulability, prolonged immobilization, staged procedures of longer than five segment levels, combined anterior-posterior approaches, ilio caval manipulation during exposure, and anesthetic time of >8 hours) and found that prophylactic IVC filter placement lowered venous thromboembolism-related events, including PE development versus population controls, and was a safe procedure with two IVC filter complications in 219 patients.³² The rate of PE in a group of spine patients with similar high risk criteria has been reported at 13.1%.³³ In the postoperative period, there should be a low threshold for ordering a computed tomogram—PE protocol to evaluate for PE if the clinical situation is suspicious. Epstein et al. found the incidence of positive computed tomography angiography-PE protocols despite negative Doppler studies to be 6.7% following cervical laminectomies/fusion and 3.6% after lumbar laminectomies/noninstrumented fusion.³⁴

■ COMMUNICATION/PSYCHIATRIC/ SOCIAL ISSUES

Informed consent is a standard part of the preoperative process. This is ideally done in the physician's office prior to the scheduled day of surgery. The International Spine Study Group looked specifically into patient's ability to recall the risks that were discussed with them. If a patient experiences a complication, they might state that they were not informed of the risks because they are unable to recall the risks. The conclusions of the study were that patients feel that the informed consent process is important, but that their ability to recall risks is poor (immediate was 41%) and worsens with time.³⁵ In this study, a 20-minute video was used to reinforce the risks of surgery. It highlights the difficulties in communication faced by physicians and patients. Less than ideal communication can result in unrealistic expectations from the surgical procedure. Communication affects each aspect of the process from the consultation in the office to the postoperative care. Davis et al. examined the experience of patients undergoing spinal surgery and identified nine main

“needs” that were important to patients. These included the need for reduced waiting times, for better information and preparation, to speak up and ask questions, to feel safe, to be proactive, to be treated with dignity and respect, and the need for ongoing support, human contact, and continuity of care.³⁶ It is important to understand that the demands on a patient who is going to be undergoing a large spinal deformity surgery, or any spinal surgery for that matter, can be very psychologically taxing. Many of these patients bring to the table a history of psychiatric problems. Polatin et al. reported that 59% of patients with chronic low back pain had concurrent depressive disorder.³⁷ Interestingly, 55% of them had depression before the onset of the pain, and 45% after the development of pain. It has been reported that the psychological status strongly influences patient reported satisfaction rating.³⁸ There appears to be a correlation between a patient having depression preoperatively and that affecting outcomes postoperatively—with multiple studies reporting poorer outcomes in patients with psychiatric disease.^{39,40} Work by Adogwa et al. suggests that, the extent of preoperative depression, independent of the surgical effectiveness, influences the reported patient satisfaction after revision lumbar surgery.⁴¹ It is thought that psychological distress deteriorates the subjective outcome of lumbosacral spine fusion and psychological screening should be an integral part of the global assessment of patients preoperatively.⁴² An important corollary to the patient with psychiatric disease is the fact that many patients with psychiatric disease will be on medications that rely on a certain blood concentration in order to be effective. In the event of a large surgery with a resulting large blood loss, there can be a drop of medication to subtherapeutic levels—which can result in the potentiating of psychotic symptoms. This has been described specifically regarding lithium, which can only be given orally—therefore taking several days to return the patient to baseline levels.⁴³ Anticipation of this situation can allow for consultation with the treating psychiatrist regarding possible drug substitutions.

The patient’s social and/or psychiatric situation may be complex. It has been found that degenerative spine disease patients with more social support and less life stress tend to have greater satisfaction in medical outcomes and overall quality of life following spinal decompression surgery compared to those who have more life stress and less social support.⁴⁴ Some adult spinal deformity patients will be in a worker’s compensation situation. Workers compensation appears to have a clear, negative influence on

outcome when compared to controls.⁴⁵ Disability compensation status, however, does not seem to have the same deleterious effect on outcomes.

NUTRITION

Nutritional status is generally recognized as a key marker of overall health and its role in successful surgical outcomes is gaining attention. Various markers can be used to gauge the nutritional level of the patients. In order to quantify a patient’s nutritional status prior to surgery—generally the albumin, prealbumin, transferrin, and total lymphocyte count or any combination of these can be examined. Unfortunately, it has been shown that a high rate of surgical patients are nutritionally depleted; this is especially true for patients of advanced age.⁴⁶ This state of nutritional need leads to immune-compromise, apathy, impaired cardiac function, reduced power, and muscle wasting.⁴⁷ These changes serve as a setup for postoperative complications and failure to thrive postoperatively.⁴⁸ It has been found that the spine surgery patients most likely to be nutritionally depleted were those that: had chronic disease, spinal cord injury, osteomyelitis, or were age 60 or greater.⁴⁹

Albumin is a protein found in the blood that correlates with overall nutritional status. It has been found that low levels of serum albumin (and also elevated BUN > 30) correlated with postoperative pulmonary problems.⁵⁰ Serum albumin of 3.5 or less was found to increase the risk of mortality, complications, wound infection, and thromboembolic disease in a series of 5,887 spinal arthrodesis patients who were evaluated from data in the National Surgical Quality Improvement Program.⁵¹

Vitamin D plays a critical role in establishing optimal bone health, which is essential for a fusion to occur. The prevalence of inadequacy in the United States has been estimated at >50% in general medicine inpatients and greater than one-third of healthy young adults.⁵² The prevalence of hypovitaminosis D in an adult orthopedic surgery population was examined in a population of 723 patients and found to be 43%.⁵³ The rates of either vitamin D inadequacy (defined as a blood level <30 ng/mL) and deficiency (<20 ng/mL) were found to be 57% and 27%, respectively, in a series of 313 patients who were undergoing spinal fusion.⁵⁴ Supplementation with vitamin D3 and calcium has been found to reduce the risk of hip fractures in elderly women, indicating that dietary supplementation is an effective intervention.⁵⁵

Based on the above studies, if preoperative testing reveals a patient is not nutritionally replete, that is an indication for supplementation. The correction of the malnourished state can be a problematic task. Strategies include early mobilization, increased consumption of calories and protein-loaded foods, nasogastric or parenteral feeds, and physiotherapy.⁵⁶ A consult with the nutritionist can be helpful. Total parenteral nutrition has been found to be helpful in the setting of staged spinal surgery patients, and it correlates with a decrease in the rates of infection.⁵⁷ Total parenteral nutrition is fraught with its own set of complications, so enteral feeding routes are preferred if possible.⁵⁸

Also deserving of mention is the patient with diabetes mellitus (DM). Diabetes mellitus is known as an important risk factor for surgical site infection in spine surgery, as DM results in an immune-compromised state—with poor polymorphonuclear function, reduced wound healing potential, and poor microvascularization.⁵⁹ Satake et al. found that proteinuria was a significant predisposing factor for surgical site infection and that these patients suffer latent nephropathy.⁶⁰ They recommended consideration of less invasive techniques in this population whenever possible. Patients can be expected to have decreased complication rates if their blood glucose is tightly controlled perioperatively.⁴³ This may require utilization of an insulin sliding scale or possibly a consult from the endocrinology service to assist in managing this challenging problem.

The other common dysfunctional nutritional state encountered is obesity. It has been documented that morbid obesity increases the risks/complications, especially for patients undergoing anterior cervical or posterior lumbar operation.⁶¹ The risks associated with obesity are multiple and include an increased risk of thromboembolic disease, problems with positioning, trouble obtaining adequate localizing films, increased incidence of wrong level surgery, increased estimated blood loss, higher rate of infection, and increased perioperative wound complications.⁶² In light of these possible complications, physicians may consider various weight reduction strategies such as dieting under physician supervision and bariatric surgery. Bariatric surgery has its own set of risks and can actually lead to malabsorptive symptoms, which can in turn lead to a decrease in BMD.

■ BONE MINERAL DENSITY

Adult spinal deformity surgery is generally performed on a population with an advanced age. This is the same

population that is generally subject to decreasing BMD and osteoporosis. Osteoporosis results in a decrease in the density and the quality of bone—which leads to an increased risk of fracture. This is a widespread problem, with an estimated 10 million Americans over the age of 50 with osteoporosis.⁶³ Chin et al. looked specifically at the incidence of osteoporosis in 1,321 patients requiring spine surgery—they found a rate of 14.5% in males over the age of 50, and a rate of 51.3% in females over the same age.⁶⁴ The assessment of the patient's BMD is a vital preoperative consideration. This assessment is accomplished via dual-energy radiograph absorptiometry (DEXA) scanning. The interpretation of these scans is based on the World Health Organizations definition for osteoporosis. The number that represents osteoporosis is a DEXA T score of ≤ 2.5 , meaning >2.5 standard deviations from the BMD of a woman at her peak BMD.⁶⁵ It is important to note that the presence of an osteoporotic fracture also grants the diagnosis of osteoporosis. Many risk factors for osteoporosis have been identified and include female sex, Asiatic and Caucasian races, old age, family history, low body weight, premature menopause, nulliparity, prolonged lactation, prolonged amenorrhea, inadequate consumption of a diet containing calcium and vitamin D, poor absorption of calcium, lactose intolerance, excessive caffeine and/or alcohol consumption, smoking, sedentary lifestyle, and prolonged treatment with thyroid hormones, glucocorticoids, anticonvulsants, aluminum antacids, and anticoagulants.⁶⁶ This list of risk factors may help the surgeon preoperatively in indicating a patient for a DEXA evaluation. These risk factors also account for possible areas of optimization of the patient perioperatively. If the cause for osteoporosis, e.g. is the result of alcoholism or smoking, then the patient may see an improvement in BMD if the alcohol and smoking are removed. Approximately 95% of the time the osteoporosis is considered primary and is related to a genetic predisposition and factors that are not modifiable, including advanced age, poor health, comorbidities, and genetic predisposition.⁴³ Osteoporosis is a risk factor for failure of instrumentation and for postoperative sacral fracture at the base of a fusion construct.⁶⁷

Current medical treatment of osteoporosis is useful, in that they can maintain even increase bone mass, but generally cannot get bone mass numbers back to normal levels.⁶⁸ Current treatment generally consists of bisphosphonates, calcitonin, estrogen, selective estrogen receptor modulators, and recombinant parathyroid hormone (PTH). The newer, anabolic agent is PTH. Intermittent PTH

administration results in an anabolic effect via the direct activation of osteoblast cell surface receptors. The value of preoperative treatment of osteoporosis with antiresorptive agents in improving rates of arthrodesis and reducing rates of instrumentation failure has not been demonstrated. Much has been published on bisphosphonates and their role in bone formation. It has been demonstrated that alendronate can positively affect the process of spinal fusion in rabbits at low doses, but has an inhibitory effect at higher doses.⁶⁹ This information is of key importance as somewhere between 10% and 35% of spine fusion procedures result in pseudarthrosis, making it the most frequently encountered complication of the procedure.⁷⁰ The complex biology of spinal fusion necessitates *de novo* bone formation and remodeling by the osteoblast/osteoclast complex. This complex is selectively targeted by osteoporosis medication, which is why these drugs are investigated thoroughly with regard to spinal fusion. Hirsch et al. looked at the literature and found that existing animal data on the effect of bisphosphonate medications is conflicting but indicates that treatment delays remodeling of the fusion mass.⁷¹ The single human study suggests improvement in radiographic parameters but contains limited clinical outcome data.⁷² In regard to PTH, though no trials in humans have been performed, the current animal literature provides evidence for a beneficial effects in terms of fusion. They recommended continuation of these therapies in patients based on their indication for osteoporosis without regard to recent or future need for a spinal fusion procedure.⁷¹

The presence of decreased BMD preoperatively may alter the surgical strategy. The surgeon may opt for techniques that limit the need for internal fixation in osteoporotic bone such as minimally invasive techniques in less severe cases. Some have advocated for prophylactic vertebroplasty to attempt to prevent either compression fractures at the top of the construct or to prevent screw cut out from the top. Pneumatics et al. reported on a cadaver experiment where they compared the effect of vertebroplasty on the compressive strength of vertebral bodies and found that the failure load for the vertebroplasty specimen was not statistically significant from the nonvertebroplasty specimens.⁷³ Lotz et al. showed that cement augmentation of pedicle screw fixation in the lumbar spine could improve pull out strength by an average of 68%.⁷⁴ Other techniques that may be applied in the osteoporotic setting include sublaminar fixation, utilizing multiple points of fixation, or circumferential fusion.

PAIN MANAGEMENT

It is not atypical for the spine patient to present on a large amount of narcotic pain medication in addition to any variety of muscle relaxants, benzodiazepines, anxiety and depression medications, and neuropathic pain medications. Many of these medications have the potential for withdrawal syndromes; some of which can be dangerous, and some of which can be deadly. In a patient with an extensive medication list, it can be helpful to consult with a pain pharmacist in order to determine the narcotic equivalents the patient is currently receiving and how to adjust that in the postoperative period. This will also help safeguard that the patient does not go into withdrawal postoperatively. Generally having the patient do a complete opioid detox prior to surgery is not a reasonable course. The pharmacist can also double-check which medications may need to be stopped prior to surgery. It is well recognized that various medications such as aspirin, dipyridamole, and clopidogrel increase bleeding risk during surgery and should be stopped prior to surgery. What is likely less appreciated is the increased hypocoagulation that is seen with other commonly used substances, specifically vitamin E containing compounds (multivitamins and nuts), glucosamine and chondroitin sulfate, ginkgo biloba, fish oils, and omega-3 fatty acids.^{75,62} All of these should be stopped prior to surgery.

In addition to the pharmacy provided pain control modalities, patients who have an implanted pain pump will also be encountered. These pumps have two major concerns: the first is concerning the dosage of opioid equivalents that they are accounting for and the second is the fact that they may be in the operative field if they are intrathecally placed. If a patient is in need of a decompression at the level where the pump is implanted, the catheter may need to be removed intraoperatively to facilitate access for decompression or it may be accidentally pulled out of its position as it may physically be in the way. In the event that it is removed, it will likely be necessary to repair the dura where the pump was inserted and also to tie off the pump so it does not continue to deliver medication. In the event that the pump is an intrathecal baclofen pump, cessation of baclofen can result in a potentially life-threatening condition.⁷⁶

It is important to confer with the patient's pain management specialists prior to surgery to establish a pain plan and also to keep the pain team involved after surgery to assist in titration of the narcotic in the acute setting as well as for the long term.

INFECTION

Infection prevention strategies for adult spinal deformity patients are variable and have not specifically been reported, though we have alluded to fact that infections are often the downstream effect of some form of weakness in another facet of the patient's health—such as their nutrition or their pulmonary function. The risk of postoperative spinal infections varies from 0.4% to 3.5%—but may be reduced with a variety of measures.⁷⁷ Pediatric spinal infection prevention was investigated via a survey of 277 pediatric spine surgeons. They found that there was significant variability in current practices. This included differences in the preoperative laboratory stratification, methicillin-resistant *Staphylococcus aureus* swabs, urine cultures, IV antibiotic coverage, use of vancomycin powder, and the use of other measure such as drains and negative pressure ventilation. It was notable that 50% of surgeons attempted home chlorhexidine use prior to surgery.⁷⁸ Unplanned hospital readmissions after spine surgeries were investigated by Schairer et al. They found a single center unplanned hospital readmission rate of 8.4% at 30 days and 12.3% at 90 days.⁷⁹ Patients with longer fusions were more likely to be readmitted. Infections accounted for 45.6% of the readmissions. Given the stress on the patient, physician, and system caused by infection, it is important to do everything possible to prevent it from occurring. Most measures have been targeted toward methicillin-resistant *Staphylococcus aureus* specifically and include measures such as nasal cultures and nasally administered mupirocin, washing with chlorhexidine gluconate 4%, the routine administration of perioperative antibiotics, copious intraoperative irrigation, instrumentation coated with antibiotics, and possibly the use of various measures to apply antibiotics topically (such as a silver impregnated dressing). The question of which of the commonly available skin preparation to use has been investigated by Savage et al, who looked at 100 lumbar spine surgery patients with CholaPrep and DuraPrep—they found that both provided comparable skin prophylaxis.⁸⁰

CONCLUSION

Preoperative planning is an important component of the process of surgical management of spinal deformity. Preoperative planning includes mapping surgical techniques and planning to ensure adequate correction of deformity. Equally important is preparing the patient medically for surgery. It is easy for the spine surgeon to focus on

creating a surgical plan for the patient, but it is paramount that the patient's medical condition and physiology be considered when developing a perioperative strategy. Each of the areas discussed above represent areas of potential optimization, which translates into a smoother operative and postoperative course and creates the situation what allows your patient to maximize their outcome potential. On the flipside, these other considerations are important because they serve as areas that if not considered can result in possibly catastrophic consequences. While it is not possible to avoid complications in adult deformity surgery completely, there are many complications that may be limited with preoperative recognition and perioperative management.

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Surgical Treatment of Adult Thoracolumbar Idiopathic Scoliosis

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Snapshot

- » Natural History
- » Clinical Presentation
- » Surgical Planning
- » Obtaining Fusion
- » Complications
- » Surgical Technique
- » Correction Maneuvers

The presentation of idiopathic scoliosis later in adulthood is commonly seen in spine practices. There are various reasons patients do not seek surgical treatment for their deformities earlier in life which include concerns over the safety of surgery, prior completed treatments with braces or other nonsurgical means, minor deformities that patient may be unaware of their existence, or not being overly concerned with their deformity at that stage of their life. While the majority of spinal deformities patients present as adolescents, many patients will present later in life due to persistent or progression of these deformities and concerns over appearance, weakness, radiculopathies, and axial back-related pains.

This chapter will discuss the natural history, clinical presentation, surgical planning, surgical controversies, and surgical techniques used to treat adult thoracolumbar idiopathic scoliosis.

NATURAL HISTORY

Surgeons should possess an in-depth understanding of the natural history of idiopathic scoliosis in order to provide the most beneficial treatment to the patient. Understanding the effect of time on the magnitude of the curve, the incidence and severity of back pain and concomitant stenosis, and the effect of the deformity on other organs is important in accurately counseling patients on appropriate treatments for their deformities.

Natural History of Curve Progression

Using data obtained of 133 curves in 102 patients over a span of 40 years, Weinstein and Ponseti published a longitudinal study on idiopathic curve patterns that revealed a significant general progression after skeletal maturity in 68% of curves.^{1,2} The spinal deformities that did not progress significantly measured $<30^\circ$ at skeletal maturity, irrespective of the curve pattern.^{1,2} In assessing thoracic, lumbar, and thoracolumbar curves, curves that measured 50° – 75° at skeletal maturity progressed the greatest compared to other curve intervals.^{1,2} Thoracic curves between 50° and 75° at maturity progressed a mean of 29.4° over this time interval; lumbar curves progressed a mean of 18.5° , and thoracolumbar curves progressed a mean of 22.3° .^{1,2} Prognostic factors for curve progression factors were also identified, but these findings may be somewhat limited due to the small study sample used, as only 10 adult patients with thoracolumbar idiopathic scoliosis were studied.¹ Nevertheless, Weinstein and Ponseti's study provided a benchmark for quantitatively understanding and predicting the progression of adolescent idiopathic scoliosis into adulthood.

Natural History of Back Pain in Scoliosis Patients

The presentation of axial back pain in adult scoliotic patients is common, but highly subjective in nature.³ Back

pain is diverse in etiology,⁴ and may be a result of spinal stenosis or degenerative discs or facets; however, patients with scoliosis are more predisposed to degenerative disc and rotatory listhesis and secondary stenosis as a consequence of their deformity. Kostuik reported an increased incidence of severe back pain in patients with lumbar curves $>45^\circ$.⁵ Jackson et al. further demonstrated a higher incidence of back pain and an increase in persistent back pain in patients with scoliosis.⁶ This back pain was associated with increased age and greater curve magnitude. Interestingly, in this series, the patients treated surgically had an overall reduction in spinal pain. Nachemson showed no increase in incidence of young adult scoliosis patients on disability when looking at a series of patients with a mean age of 23 years.⁷ However, in the subgroup analysis, the presence of rotatory listhesis was higher with increasing age and more common in patients with lumbar curves. Furthermore, increased curve magnitude and increased age were associated with a higher incidence of back pain.

Effect of Scoliosis on Other Organs

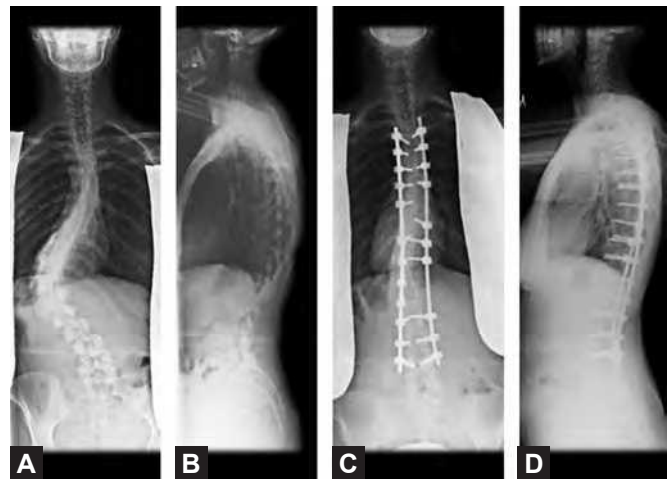
The effect of scoliosis on pulmonary function following maturity is not well known. Authors have demonstrated a decreasing forced vital capacity (FVC) with increasing curve magnitude.^{8,9} In this group, the FVC in patients with curves $>70^\circ$ was below the national threshold. Older reviews demonstrated a higher mortality rate, up to twice the national average, in long-term follow-up of patients with severe spinal deformities.¹⁰ In clinical practice, we rarely encounter patients with medium to large curves with clinically significant organ dysfunction.

CLINICAL PRESENTATION

In the clinical practice, there are four common presentations seen in the assessment of adult thoracolumbar idiopathic scoliosis. Patients generally present in their early adulthood with the primary complaint of deformity, later in adulthood with established degenerative changes with or without neurological claudication, or following remote surgical treatment of scoliosis with adjacent segment degeneration, stenosis, and/or alignment issues.

Presentation in Early Adulthood

Deformity, with or without pain, is the primary reason why young adults seek assessment for scoliosis.¹¹⁻¹³ Functional limitations of living with scoliosis and the psychosocial importance of physical appearance might be factors that contribute to the patient's desire to pursue surgical assessment. The main indicator for surgery in this group is



Figs. 113.1A to D: Standing posteroanterior (A) and lateral (B) long cassette radiographs of a 39-year-old presenting with back pain and deformity secondary to a 60° left thoracolumbar scoliosis. Correction is achieved with a posterior T4 to L4 construct with satisfactory alignment in both the coronal (C) and sagittal planes (D).

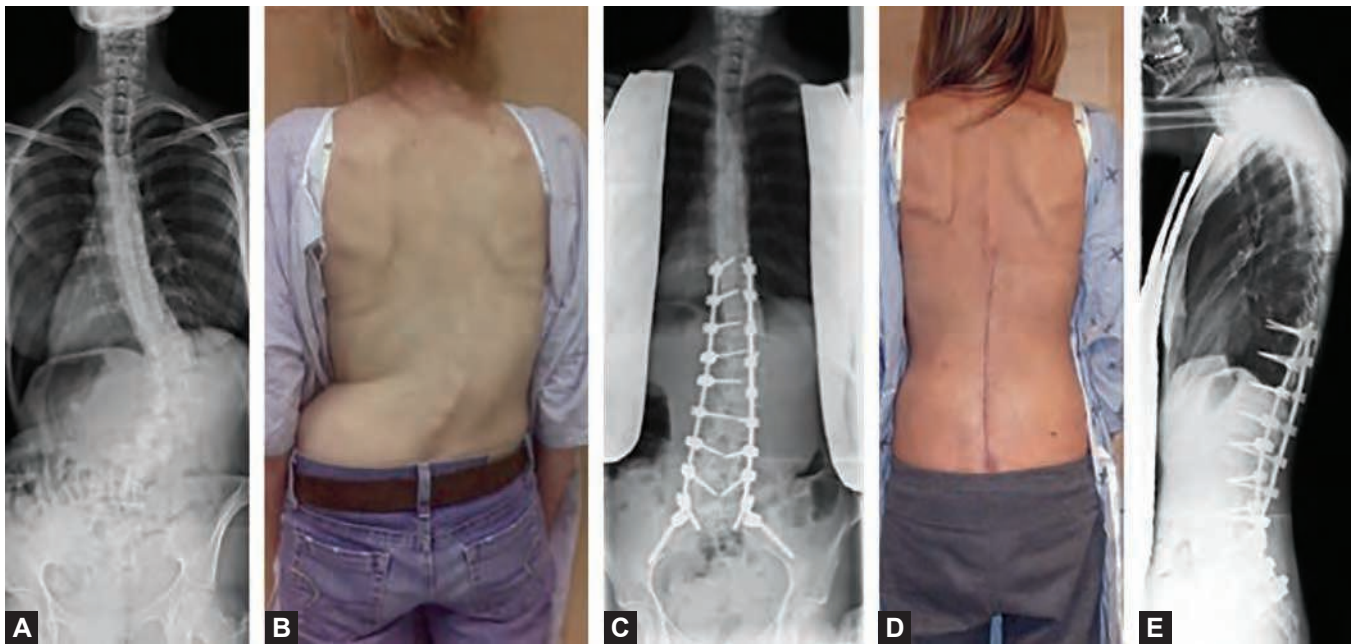
the baseline degree of the deformity or progression of the curve. While some of their pain may improve from surgery, future problems associated with multilevel fusions have to be considered prior to engaging in surgical treatment.

The surgical management of idiopathic curves presenting over the age of 18 can be treated in the same manner and with the same decision making used in treating adolescent curve patterns. Further growth is no longer of concern. In cases without significant disc or facet degeneration, a similar decision process is utilized concerning level selection and surgical approach is employed (Figs. 113.1A to D).

Presentation with Established Degenerative Changes

Older patients with degenerative progression may exhibit mechanical back pain as a result of secondary changes to the discs and/or facets. Rotatory listhesis is often seen at the distal end of the curve, where the most tilted vertebra subluxes on the distal spine. Maximizing nonsurgical treatments in this setting in the form of physical therapy, massage treatments, activity modifications, injections, and medications are the main recommended treatments.¹⁴⁻¹⁶

When surgery is considered, the surgery should address both the deformity and the associated levels with symptomatic degeneration.¹⁷⁻¹⁹ Workup with appropriate imaging that includes computed tomography (CT) scan and magnetic resonance imaging (MRI) to clearly define the pathology is imperative to improving surgical outcome (Figs. 113.2A to E).



Figs. 113.2A to E: Standing posteroanterior (A) and clinical (B) of a 46-year-old woman with a right lumbar scoliosis demonstrating lateral listhesis of L2 on L3 and L3 on L4. Significant degeneration of the L4-L5 and L5-S1 levels necessitated a construct that extended from T10 to the pelvis (C). Clinical postoperative photograph (D) shows a nice cosmetic correction of the rib on pelvis deformity with a well-aligned torso, with a balanced sagittal plane (E).

Stenosis Patterns with Scoliosis

Stenosis patterns are quite typical in scoliosis. Stenosis will be more prominent on the concave side of the curve. For left convex lumbar curves with a mid-lumbar apex, stenosis will occur in the upper lumbar roots on the right; however, the lower roots will be affected by the lumbosacral fractional curve, which will be apex to the right. This will result in left-sided stenosis symptoms. The stenosis from the fractional curve is generally more prevalent than those caused by the main curve. This leads to the paradoxical symptoms of left-sided stenosis symptoms with a left-sided lumbar curve (Figs. 113.3A to K). The stenosis can involve both the subarticular region and the foramen. Patients may develop degenerative facets with an associated degenerative spondylolisthesis that can lead to bilateral stenosis as well.

Surgical treatment for this group will consist of correction of the curve and decompression of the levels with stenosis. A clear understanding of the regions of nerve compression is imperative prior to surgery. While some of the areas of stenosis will decompress with the deformity correction, others will need to be formally decompressed. Appropriate preoperative cross-sectional imaging with

MRI, CT scan, and occasionally, CT myelograms will provide the necessary imaging for appropriate planning.

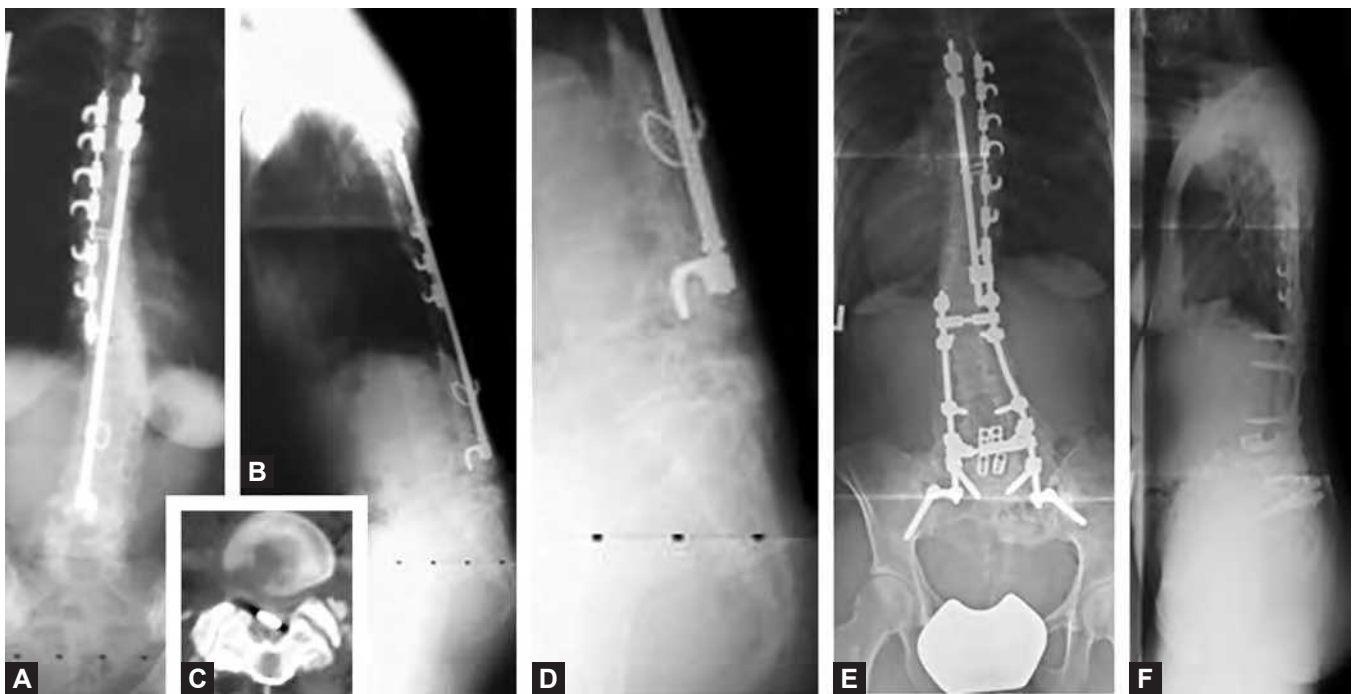
Revisions

Patients previously treated surgically for scoliosis are at risk of degeneration of the remaining mobile segments.^{20,21} Patients may present with or without residual coronal and/or sagittal misalignment compounding the distal degeneration. Stenosis may or may not be present as described in the previous section. Generally, constructs ending with a laminar hook in the canal will have an added source of stenosis that may need to be addressed (Figs. 113.4A to F).

Common issues related to revisions include the patient's global alignment, the residual coronal and sagittal alignment of both the fused and nonfused segments, the number of unfused segments remaining, the presence of degeneration, and/or stenosis with or without listhesis in some or all of the remaining levels. Planning how proximal and distal to extend your construct, if and where osteotomies are required, where or if to connect to the previous construct, and the metal type and name of the previous instrumentation system, will greatly improve the flow of the revision and ensure that the appropriate equipment is available for the procedure.



Figs. 113.3A to K: Spinal stenosis in the setting of a coronal plane deformity will develop on the concave side of the curve. For example, a lumbar curve with a right convex apex at L1-L2 (D), stenosis will develop on the left concave aspect at the curve apex (B and C). Because of the main curve, a secondary fractional curve develops in the lumbosacral region with an opposite configuration to the main curve. This results in lumbosacral stenosis on the right side (E to G), which is the concave side for the lumbosacral fractional curve. Because the distal lumbar levels are more prone to stenosis secondary to smaller foramina and underlying degeneration, nerve compression most often occurs in the fractional curve. Note the wide open foramina in the lower lumbar region on the convex left (A) compared to the tight distal foramina (G) on the concave side of the fractional lumbosacral curve. For these reasons, a right lumbar degenerative scoliosis with an upper lumbar apex will most often lead to right-sided neurological symptoms of the distal lumbar roots. Standing preoperative anteroposterior (H) and lateral (I) radiographs demonstrate the deformity, which was treated with a posterior T4 to pelvis procedure with L4 to sacrum decompression and interbodies as seen on the postoperative PA (J) and lateral (K) radiographs.



Figs. 113.4A to F: A 35-year-old patient presents 22 years following a T4 to L4 Harrington fusion. Anteroposterior (A) and lateral (B) demonstrate a solid construct with a Harrington flat back deformity. Inset (C) shows advanced degeneration and stenosis at L5-S1. Middle figure (D) demonstrates a close-up lateral of the lumbosacral region. Following extension of the fusion to the sacrum and pelvis (E, F) with L4 to S1 decompressions and interbody fusions, sagittal alignment was restored.

SURGICAL PLANNING

Fusion Levels

Patients presenting with deformity without significant degenerative changes can be treated with the same fusion levels that would be considered for adolescent curves. Degenerative changes present in the region of the main deformity would be addressed with the correction of the deformity. When the degenerative changes occur outside the intended fusion levels, consideration has to be made whether or not these levels should be included in the construct. Clinical judgment, MRI and CT findings, presence of nerve compression, flexibility of the unfused segments, and the number of remaining motion segments are factors that will be considered when deciding the proximal and distal levels of the construct.

Stopping at L5 versus S1

Determining the lower instrumented level is a significant controversy in adult deformity.²² More motion segments preserved can theoretically distribute the loads through more disc levels and minimize the need for early revision of distal degeneration. However, the alignment of the remaining motion segments is a contributing factor as well, and perhaps having less perfectly aligned levels may in fact last longer than more poorly aligned segments. These judgments are still open to debate.

If multiple levels cannot be preserved, the surgeon and patient must decide whether it is feasible to stop the fusion at L5 or to extend the construct to the sacrum. Stopping at L5 will preserve one motion segment, and may facilitate fusion at the instrumented segments by allowing outlet motion through the L5–S1 level. A positive for ending the construct at L5 is that it has been associated with a lower complication rate, less blood loss, lower transfusion rates, and shorter operative times.²³ However, at 3–5 years of follow-up, 15% (4/27) of these highly selective cases showed degeneration at the L5–S1 level, with the rate increasing to, 69% of cases (18/26) at 5–20 years of follow-up.²⁴ In this series, risk factors for degeneration included sagittal vertical axis ≥ 5 cm, circumferential fusions, and longer constructs (upper instrumented vertebra of T1 to T7).

Criteria for Stopping at L5

1. Sagittally and coronally balanced patient
2. No or minimal degeneration of the L5–S1 disc and facets
3. No coronal tilt to L5
4. No previous surgery at L5–S1 (i.e. L5 laminectomy)
5. No anterior listhesis at L5–S1
6. Good bone stock with excellent fixation in L5.

Distal Fixation with Long Fusions to the Sacrum

If the above criteria cannot be met, one should consider extending the fusion to the sacrum. However, with these longer constructs, the forces at the sacrum are very large due to the longer lever-arm. This creates a large flexion moment through the sacrum that could result in sacral fracture or sacral screw pullout, plowing, or loosening. Protecting the sacral screws with further distal fixation can negate some of these forces and provide the stability required to promote fusion. Commonly utilized techniques of distal fixation include iliac wing screws, S2 iliac screws, and iliosacral screws.^{25,26}

OBTAINING FUSION

Obtaining a solid fusion in a long deformity construct extending to the sacrum presents a significant challenge. There are multiple factors involved in creating an environment to promote fusion.

Biomechanical

- Adequate fixation throughout the construct
- Balanced spine in the sagittal plane
- Balanced spine in the coronal plane
- Anterior column support at high-risk levels (L4–L5, L5–S1, levels with large disc heights)
- Consideration of the position and balance of the non-fused spine
- The patient's bone density.

Biological

- Adequate bone graft (local, autograft, allograft)
- Adequate vascularized tissue in region (muscle coverage, decorticated host bone)
- Role of bone graft adjuvants and extenders.

Surgical Approach: Anterior versus Posterior versus Combined

Several authors approach all spinal deformities through a posterior approach. The posterior approach provides for exposure of the spine at all levels, while simultaneously allowing decompression of regions of stenosis, multiple fixation options with either screws, hooks, or wires, and correction of the deformity. It is the most familiar approach of the majority of spine surgeons. Interbody support can be achieved below the conus to help facilitate release and

fusion. Furthermore, posterior-based osteotomies including the Ponte or Smith Petersen, and three column osteotomies when needed, can be performed.

The role for anterior surgery in adult scoliosis surgery is evolving. Anterior surgery can be useful as the primary approach in selected Lenke V curves in younger patients with good bone stock, well preserved distal levels, and flexible, nonstructural secondary curves. The use of direct lateral approaches can facilitate correction and fusion in smaller, flexible lumbar curves, when used with either standard posterior or minimally invasive posterior techniques to supplement fixation. As well, formal anterior lumbar interbody fusions can be done at multiple levels in the lumbar spine to provide both realignment of the sagittal and coronal planes and supplement fusion of longer posterior constructs. The morbidity of the anterior approach including denervation of the abdominal wall, potential injury to major vessels, retrograde ejaculation in males, and others must be weighed against the potential benefits in fusion rates and correction.

■ COMPLICATIONS

Common spine complications in adult scoliosis surgery include pseudarthrosis, proximal junctional failure, and infection.²⁷⁻³⁰ Medical complications can occur frequently especially in patients with other comorbidities.³¹ The complication rate in adult deformity surgery can be quite high.³²⁻³⁶ Smith et al.³⁷ in a retrospective review of 206 of 453 patients showed that patients between the ages of 65 and 85 had a mean complication rate of 71% (29% major) compared to a rate of 42% (15% major) in patients between the ages of 45 and 64, and a rate of 17% (6% major) in patients between the ages of 25 and 44. Sansur et al.,³⁸ in a review of the Scoliosis Research Society database of close to 5,000 cases, noted a 13.4% short-term complication rate, with a higher incidence noted in patients undergoing osteotomies, revisions, and combined anterior, and posterior approaches.^{33,39-42} Mok et al.⁴³ noted a 26% reoperation rate in 89 patients, and Howe et al. a revision rate of 35% in 103 patients. The rate of proximal failures has been reported up to 26%.^{33,44,45}

Despite the high complication rate, outcomes from the procedure were satisfactory with Oswestry Disability Index scores improving from 43 to 24, SF-12 PCS improving from 27 to 37, back pain improving from 6.7 to 2.6, and leg pain improving from 4.9 to 2.0 in patients over the age of 65.³⁷ The expected clinical course following the surgery must be carefully delineated in advance so that the procedure can meet or exceed the patient's expectations.

■ SURGICAL TECHNIQUE

Anterior

Stand-alone anterior constructs are indicated for the young adult with a Lenke V curve pattern. A standard thoracoabdominal approach on the convex side of the curve (generally left) is performed. The fixation should extend from a minimum of the neutral vertebra to the neutral vertebra. Discectomies are performed and it is recommended to place an interbody support to maintain normal sagittal alignment through the region of fusion. Some surgeons advocate a dual rod construct on the convexity, and combination of derotation and compression is performed to achieve correction. Leveling out of the lower instrumented vertebra in the coronal plane is important to maximize the longevity of the distal nonfused motion segments. Failure to maintain the normal sagittal alignment through the construct will lead to hyperlordosis of the nonfused levels and increased loading of the distal facets (Figs. 113.5 and 113.6).

Minimally Invasive

Direct lateral approaches have been popularized for smaller lumbar deformities. The importance of appreciating the relationship of the vessels and exiting nerves is paramount with this approach, and even more important in the presence of scoliosis. For a left lumbar, the concave right side leaves a very narrow safe zone between the exiting nerve root and the vena cava (Fig. 113.7). The angle of the disc space in relation to the proximal extent of the iliac wing needs to be considered as well with regard to the feasibility of the approach. The presence of degenerative concave endplate osteophytes can complicate the approach as well. Lastly, the relationship of the genitofemoral, lateral femoral cutaneous, obturator and femoral nerves on the psoas muscle need to be considered as they will run through the "safe zone".⁴⁶⁻⁴⁹ Preoperative planning of the particular anatomy in a given case will help in deciding whether a concave lateral approach is feasible.⁵⁰ An excellent description of the relevant anatomy of the lateral approach in adult deformity surgery is well described in papers by Mundis et al.⁵¹ and Regev et al.⁵² Adjuvants to scoliosis surgery, such as intraoperative skull and skeletal traction, may correct the curve sufficiently intraoperatively to allow for safer access to the disc spaces.

Supplemental posterior fixation is recommended to supplement the direct lateral approaches. These can be done percutaneously or open. The choice of posterior levels to be instrumented should be the same regardless whether done percutaneously or open. When extending



Figs. 113.5A and B: Lumbar preoperative (A) lateral radiographs of a 21-year-old patient who underwent an anterior scoliosis correction. Anterior convex compression led to thoracolumbar kyphosis with compensatory hyperlordosis of the remaining lumbar mobile segments. Following three column osteotomy of her fusion mass (B) the thoracolumbar kyphosis is corrected. Lumbar hyperlordosis is no longer required to maintain an upright posture.

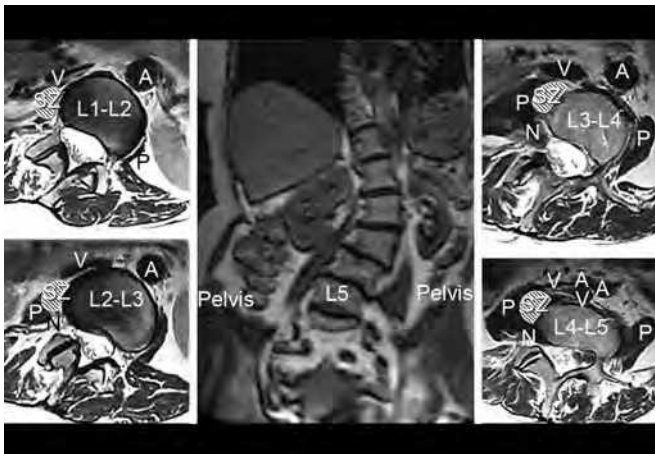
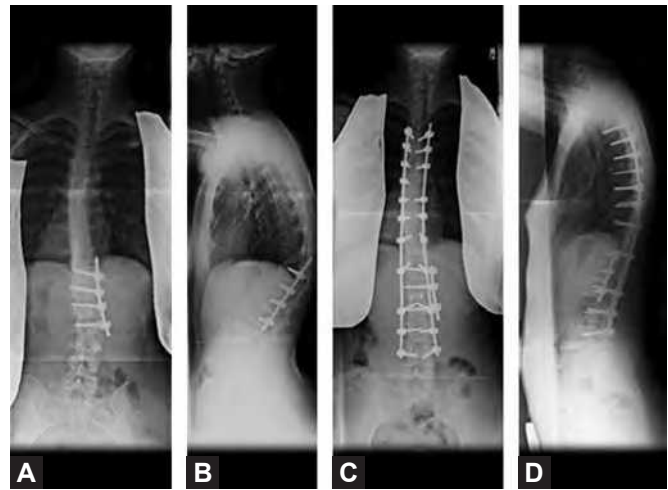


Fig. 113.7: MRI depicting the anatomy for safe zones (SZ) around the main arteries (A), veins (V) and nerves (N) with relation to the psoas (P) for access for anterior or lateral surgery in lumbar scoliosis in a typical left lumbar curve pattern. The psoas increases in volume and in its ventral extension as it travels distally in the lumbar spine. A narrow SZ is present on the right concavity between the inferior vena cava (V) and the exiting nerve roots (N) at L1-L2, L2-L3 and L3-L4. A much safer access is present on the left side at these levels. At L4-L5, the prominent psoas abuts the major venous structures ventrally on the right, leaving access to the disc space either through the transpsoas approach or through posterior retraction of the psoas muscle.



Figs. 113.6A to D: Preoperative standing posteroanterior (A) and lateral (B) views of the patient depicted in Figure 113.5. A pedicle screw-based construct extending from T4 to L4 was performed restoring her coronal (C) and sagittal balance (D).

the fusion to the sacrum, the addition of interbody support at L5–S1 is recommended.^{53,54} The minimally invasive technique is still in evolution and long-term results and outcomes need to be better investigated to determine how and where this method fits in with the spectrum of scoliosis treatment.

Posterior

Posterior approaches are the mainstay of treatment of adult deformity. It allows easy access to the canal, the foramen, and the iliac wings. Interbody fusions and osteotomies can supplement the procedure when indicated. Pedicle screw constructs offer excellent multiplanar fixation and facilitate deformity correction in multiple planes. A large variety of implant systems are available. Titanium systems offer a variety of rod options from the softer commercially pure titanium, to the medium stiffness titanium alloy, to the stiffer cobalt chrome rods. Rod stiffness can be adjusted by increasing or decreasing the rod diameter or the implant density. Titanium-based implants can be connected to the cervical spine and offer minimal artifact with MRI imaging. Stainless steel was the system of choice in the past; however, cobalt chrome rods offer similar biomechanical properties to go along with the benefits of titanium-based systems.

Goals of Surgery

- Decompression of regions of stenosis
- Level L5 in the coronal and sagittal planes

- Sagittal balance (i.e. lumbar lordosis within 10° of the pelvic incidence)
- Improved coronal curve magnitude
- Neutral transition to unfused segments
- Stable fixation
- Biological and biomechanical environment conducive for fusion.

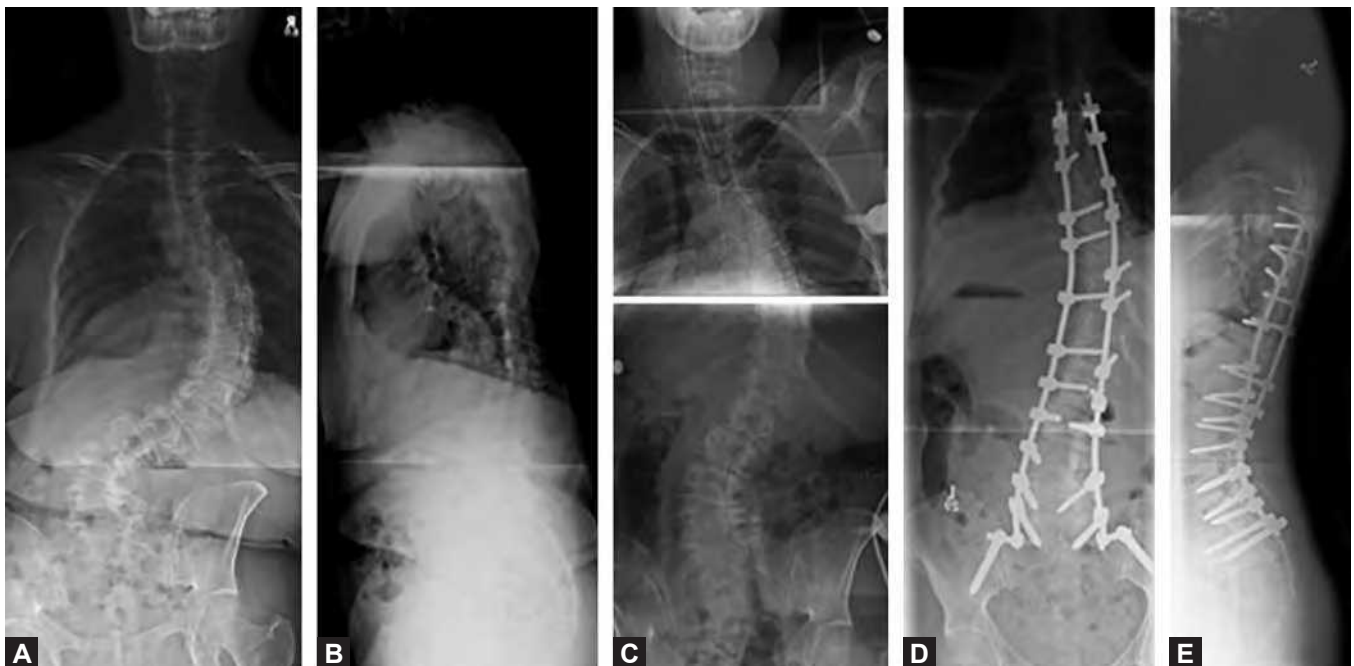
CORRECTION MANEUVERS

When fusing to the sacrum with pelvic fixation, it is important to ensure that the rod takeoff from the sacrum is parallel to the long axis of the patient. Connecting the rod to the pelvic fixation and the S1 screw can inadvertently result in an unwanted coronal offset that will cause coronal imbalance. Similarly, correcting the main lumbar curve without leveling off the lumbosacral fractional curve will lead to coronal imbalance to the side of the convexity. For this reason, I prefer to place the concave rod of the main curve in first. This has the benefit of compressing the convexity of the lumbosacral fractional curve, to help level off L4 and L5 in the coronal plane before correcting the main curve, which is generally more flexible. Alternatively, inter-body support in L4–5 and L5–S1 can help to level these levels prior to placing the rods. In either case, leveling L4

and L5 should be a priority prior to correcting the main curve to maintain coronal balance.

For sagittal alignment, the key is to adequately bend the rod to conform to the desired sagittal plane. For this, it is important to be familiar with the mean segmental sagittal plane angulations of the thoracic and lumbar spines.⁵⁵ The T12–L1 level is neutral with lordosis increasing each level to the sacrum. Approximately two-thirds of the normal lumbar lordosis occurs between L4 and S1. From T10 to T12 there is approximately 5° of kyphosis, assuming normal thoracic kyphosis. The rod bend should reflect this. Securing the fixation to the appropriately contoured rod will correct the deformity and provide a balanced sagittal plane, assuming the rod is stiffer than the spine. For stiffer curves, the addition of posterior column osteotomies and potentially anterior releases can provide the flexibility required to correct the deformity.

Cantilever and translational maneuvers provide powerful correction of the deformities. Derotation maneuvers are useful in younger patients; however, significant loss of fixation can occur in patients with poorer bone stock. In situ bending techniques provide strong coronal correction; however, this is often at the expense of the sagittal plane. Intraoperative traction can facilitate the correction as well^{56–58} (see Figs. 113.8A to E)



Figs. 113.8A to E: Preoperative standing posteroanterior (A) and lateral (B) radiographs of a 65-year-old lady presenting with back and leg pain secondary to her spinal deformity. Intraoperative skull-skeletal traction was used as depicted in (C) providing initial correction of the deformity. Further leveling of L4 and L5 with a posterior T4 to pelvis construct restored the coronal (D) and sagittal (E) alignment.

SUMMARY

The treatment of adult thoracolumbar scoliosis is still in evolution. Techniques are continuously undergoing refinement. Powerful posterior correction systems allow for excellent corrections, especially when combined with releasing osteotomies. Despite the improved corrections, multiple controversies persist and complications and long-term outcomes are not as good as we would like. A better understanding of the principles of sagittal alignment has helped surgeons to provide more balanced spines; however, as yet, this has not translated into lower proximal failure or higher fusion rates. Working hard to maximize nonsurgical treatment, careful selection of appropriate surgical candidates, and educating patients on the realistic expectations of surgery will help improve patient satisfaction and outcome.

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Surgical Management of Adult Lumbar Degenerative Scoliosis

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Snapshot

- » Natural History
- » Conservative Treatment
- » Indications for Surgery
- » Surgical Plan
- » Surgical Technique
- » Results and Complications
- » Postoperative Management

INTRODUCTION

Adult lumbar degenerative scoliosis (ALDS) has been increasing in prevalence in a large part due to the rising life expectancy of the past few decades and the existing elderly population. The prevalence of ALDS is reportedly anywhere from 1% to 10% of the population with new onset deformity seen in >30% of individuals after the age of 40. This has reenergized discussion of treatment principles and treatment innovations for lumbar degenerative scoliosis.

NATURAL HISTORY

Adult degenerative scoliosis is typically diagnosed in patients older than 40 years of age. These patients do not possess a history of adolescent idiopathic scoliosis and as such, this condition is often referred to as *de novo* degenerative scoliosis. The associated deformity is generally thought to develop as a result of asymmetric degeneration of discs and facet joints, an entirely separate process from that of adolescent idiopathic scoliosis of the young and growing spine.¹⁻³

Patients with ALDS may develop significant symptoms of axial or mechanical low back pain, leg pain and neurogenic claudication, as well as spinal imbalance.^{4,5}

Generalized axial back pain may be related to muscle fatigue, facet joint arthrosis, disc degeneration, and the loss of lumbar lordosis.⁶ Neurogenic claudication or radiculopathy is often secondary to central, lateral recess, or foraminal stenosis or neural compression due to the spinal deformity.

Symptoms from spinal stenosis in ALDS are not generally relieved by forward flexion, as has been noted in those with neurogenic claudication and spinal stenosis not associated with scoliosis. Instead, symptoms of spinal stenosis in those with ALDS may be relieved by the patient sitting and supporting his trunk with both arms. This distinction is important because the prognosis and treatment of ALDS are different from those with degenerative spinal stenosis.⁷ In ALDS, nerve root compression is often caused by pedicular kinking on the concave side with nerve root stretching on the convex side. Liu et al.⁸ confirmed that the L3 and L4 roots were more commonly compressed by foraminal or extraforaminal stenosis on the concave side of the curve, whereas the L5 and S1 roots were affected by lateral recess stenosis on the convex side. The magnitude of the Cobb angle, however, has not been shown to correlate with symptom severity.^{6,10}

As with all pathology related to the spine, the decision to pursue operative treatment for ALDS is primarily based

on severity of symptoms and disability. Self-assessments of health and disability, such as Oswestry disability index (ODI) and SF-12, can be useful adjuncts in decision making in ALDS. Fu et al. found that those patients electing for operative intervention generally reported worse health and greater disability than those initially treated with conservative therapy.⁹

■ CONSERVATIVE TREATMENT

Conservative or nonoperative treatment is initiated with anti-inflammatory medications, activity modification, physiotherapy, and bracing. Conservative treatment is more often successful for small curves <20° with <2 mm of lateral subluxation. These patients typically have fewer symptoms of neurogenic claudication or back pain. The efficacy of conservative treatment, however, is not firmly supported by literature. Interventional techniques like denervation of the facet joints with medial branch radio-frequency ablation, and transforaminal root blocks have been tried with varying results.

■ INDICATIONS FOR SURGERY

Patients in whom nonoperative management has failed are considered candidates for surgical treatment. Specific indications for surgery in adult patients with degenerative lumbar scoliosis may include:

- Progressive deformity
- Progressive leg pain or other neurologic manifestations
- Functional difficulties secondary to spinal imbalance
- Cardiopulmonary compromise secondary to severe spinal deformity
- Unsatisfactory cosmetic appearance secondary to spinal deformity*
- Persistent back pain failing conservative care*

A subset of patients with ALDS is often discovered on routine physical examination and is asymptomatic and therefore requires no treatment. Only a fraction of elderly adults with scoliosis ultimately elects for surgical treatment. Glassman et al.¹¹ found that the presence or absence of medical risk factors correlates with the decision to undergo corrective surgery, with nonoperative patients likely to have more risk factors. Similar to adolescent idiopathic scoliosis curves that can progress into adulthood without treatment, ALDS curves also tend to progress 1–6°

per year. This is especially true for those patients whose curves possess Cobb angles >30°–40°, an apical rotation greater than grade II, a lateral listhesis >6 mm, and an intercrestal line through the L-5 body.¹² Birknes et al.¹³ also noted that adverse prognostic factors for curve progression include curve magnitude >30°, osteoporosis, and lateral listhesis especially at the L3 and L4 segment.¹⁴

Progression of neurologic symptoms is an indication for surgical intervention.¹² Central stenosis can be successfully decompressed using a mid-line sparing hemilaminotomy technique in patients without major lateral subluxation or sagittal plane instability. In contrast, lateral recess or foraminal stenosis decompression solely on the concave side of a lumbar scoliotic curve is often inadequate owing to either insufficient correction of deformity or iatrogenic destabilization. Rotatory listhesis in and of itself results in neural compression and is believed to be a causative factor for back pain as well as radicular symptoms. Realignment of rotatory subluxation contributes to nerve root decompression and improvement in truncal imbalance that ultimately may result in relief of leg pain.¹⁵

From a mechanical perspective, low back pain is caused at least in part by facet joint arthrosis, disc degeneration, and the loss of lumbar lordosis.⁶ In most cases, nonoperative treatment is sufficient to relieve pain and restore patients with a painful deformity to their normal activities.¹⁶ For those patients with intractable back pain despite concentrated nonoperative therapy, surgical treatment may be an option although predictive relief of low back pain has not been widely reported in the literature.¹⁷ Appropriately selected ALDS patients for surgical intervention have been shown to demonstrate significant improvement in symptoms.^{18–20}

Sagittal imbalance often leads to muscular discomfort and symptomatic axial low back pain. Consequently, in order to relieve low back pain, in addition to the other necessary surgical requirements such as stenosis decompression, restoration of sagittal balance is recommended. Meaningful neural element decompression for patients with sagittal imbalance and instability is a precarious undertaking as decompression alone may lead to further deformity or instability. Important factors to consider when contemplating surgical intervention include the length of the degenerative segment, the patient's bone mineral density, the stiffness of the curve, the degree of sagittal and coronal imbalance, and the size of the patient.^{21,22}

* One must exercise extreme caution as cosmesis and back pain in isolation are not strongly supported in the literature and have highly variable success rates.

SURGICAL PLAN

If surgery is contemplated it is done so following a discussion with the patient of the risks and benefits of surgery and a critical evaluation of the patient's true complaints and physical limitations. Most often, the goals of surgery include relief of leg and back pain and correction of deformity.

To improve patient function, two basic goals need to be attained: a thorough decompression of the involved neural elements and reestablishment of both coronal and sagittal balance.²² Silva and Lenke⁷ suggested six distinct levels of operative treatment that are available for patients with symptomatic adult degenerative scoliosis:

1. Decompression alone
2. Decompression and limited instrumented posterior spinal fusion
3. Decompression and entire lumbar curve instrumented fusion
4. Decompression with anterior and posterior spinal instrumented fusion
5. Thoracic instrumentation and fusion extension
6. Inclusion of osteotomies for specific deformities.

Studies have shown that decompression alone is associated with the lowest blood loss, the shortest hospital stay, the fewest complications, the least need for revision surgery, and an improvement in the mean ODI.^{4,14,23} Decompression alone, however, is usually not recommended because it can lead to the progression of deformity and worsening of symptoms, especially at the apex of the degenerative curve.²⁴⁻²⁶ It is usually only suitable for those patients with neurogenic claudication due to central stenosis requiring a limited decompression. Silva and Lenke⁷ emphasized that posterior decompression alone is advisable only for patients with anterior osteophyte formation, <2 mm of subluxation, reasonable sagittal and coronal balance, no axial back pain, and a curve <30°. If a limited decompression alone is found to be appropriate, great care must be taken to preserve the pars interarticularis and associated facet, removing only what is necessary for decompression. If, however, a more extensive decompression is found to be necessary and the stability of spine is compromised, arthrodesis techniques warrant consideration. Pursuable options include anterior, posterior, or combined anterior and posterior lumbar procedures.^{5,26} Determining the extent of the fusion is the most important aspect of this surgery and Simmons et al. recommended the following principles when surgical intervention is indicated:²⁷

- Instrumentation should not end at the apex of a kyphosis or a spondylolisthesis
- Any level of severe rotatory subluxation should be included in the fusion
- To balance the spine, the most horizontal vertebra should be chosen as the upper instrumented vertebra (UIV). This may not always be necessary as sometimes only the apex of the deformity is fused but the supra-adjacent disc should not be severely degenerated

Decompression and short-segmented instrumented fusion within the deformity is performed in instances where the Cobb angle is <30° or where minimal lateral listhesis of the vertebral body is present. For these patients, the instrumentation should be limited to the levels of the decompression. This type of limited fusion may help to reestablish the stability of spine for patients with iatrogenic imbalance owing to decompression. Notably, this treatment is advised in patients without significant axial back pain, symptoms related to the deformity itself, and/or move up significant coronal or sagittal imbalance.^{7,14}

Long-segmented instrumented fusion and deformity correction are appropriate for patients with a higher Cobb angle in addition to coronal and sagittal imbalance.²⁵ Decreased lumbar lordosis and poor sagittal balance have been correlated with pain and functional loss. Clinically correlating pain with the location of the curve becomes very important in terms of selecting the appropriate operative treatment. More specifically, axial back pain correlates most with L-3 and L-4 endplate angulation, loss of lumbar lordosis, thoracolumbar kyphosis, and lateral listhesis.^{6,7,15,28} For this reason, the entire lumbar curve is included in the instrumented fusion subsequent to any necessary decompression procedure when axial back pain can be associated with the spinal deformity.

Compared to short segment fusion, long segment fusion has proven better in correcting scoliotic curvatures and has provided a greater advantage in improving rotational subluxation of the apical vertebra.⁴ Decompression and long segment instrumentation may help to relieve low back pain as well as the symptoms of neurogenic claudication. Radiculopathy secondary to foraminal stenosis may be relieved indirectly by correcting the deformity itself. This is especially true of the L-3 and L-4 roots that are typically compressed by foraminal or extraforaminal zone stenosis on the concave side of the curve. Unfortunately, even with long fusions, restoration of sagittal alignment in the absence of an osteotomy may be more difficult to perform in the aged spine.^{5,29}

For patients with decompression and long segment instrumentation, determining the extent of the fusion is critical in order to prevent spinal instability and progression of deformity. There has been significant debate on the extent of proximal instrumentation. This has especially been the case in situations of higher grade deformity: Cobb angle $>30^\circ$, loss of sagittal balance with reduced lumbar lordosis, and severe curves extending into the lower thoracic zone such as T-11 or T-12. Suk et al. have suggested extending the proximal fusion to T-10 level in general due to an increased risk of proximal junctional kyphosis when fusion is only extended to the T-11 or T-12 level. The T-11 and T-12 vertebral levels have floating ribs, and therefore are not stable zones to end fixation.

Proximal fusion levels should start at the neutral and stable vertebrae, as defined by the central sacral vertical line. If the coronal plane deformity allows, the UIV should be normalized in the coronal plane, aligning the superior endplate and the adjacent disc in the horizontal plane. Theoretically, this should decrease shear forces associated with a disc space that is skewed in the coronal plane. The proximal extent of fusion should therefore allow for both restoration of the sagittal alignment within the instrumented segments and should serve as the transition to normally aligned proximal vertebral segments in the sagittal plane. Some surgeons will end the fusion above the apex of the curvature but within the curve as long as the disc above is symmetrical and not severely degenerated.

Cho et al. noted that neutral vertebrae, rather than stable vertebrae, were found most often at T-11 or T-12 in the setting of a degenerative scoliotic curve. They also noted similarly that fusion to T-10 was more reliable compared to fusion to T-11 or L-1 due to the extra stabilization the ribs offered at the thoracolumbar junction. Stopping the fusion at L-1 or L-2 resulted in the highest incidence of proximal adjacent segment disease, whereas fusion to T-10 had the lowest incidence. From a biomechanical perspective, true nonfloating ribs tend to increase the stability of the thoracic spine through the thoracic rib cage. The rib cage effectively lengthens the transverse dimensions of the spine, giving the thoracic spine greater resistance to moment forces in the sagittal, coronal, and axial planes. The upper 10 thoracic vertebrae (T-1 to T-10) obtain this mechanical support through the true ribs, but T-11 and T-12 have floating ribs without costosternal articulation. These levels lack the ligamentous support provided by the costovertebral, costocorporeal, and costotransverse articulations. Hence, stopping at or distal to the T-11 and

T-12 levels puts the adjacent segment at a biomechanical disadvantage. Interestingly Cho et al. were unable to demonstrate a significant difference in the rate of proximal adjacent segment disease with fusion to T-10 versus fusion to T-11 or T-12. They found that proximal adjacent segment disease occurred more commonly when the fusion stopped at or below the upper end vertebrae of the deformity in the coronal plane. The neutral vertebra was found to adequately represent the UIV.

Driven in part by the concern that a fusion to the sacrum can lead to subsequent degeneration of the sacroiliac joint, altered gait mechanics, and an increased pseudoarthrosis rate, the sacrum is often excluded from the fusion construct when possible. If fusion to the sacrum is indicated, a combined approach is recommended to maximize the fusion rate, reestablish lumbar lordosis, and to prevent implant failure across the lumbosacral junction. Bridwell et al. recommended only including the sacrum in the fusion construct when there exists: a spondylolisthesis at L5-S1, stenosis at L5-S1, a prior laminectomy at L5-S1, or an oblique takeoff at L5-S1. Cho recommended that a fusion should stop at L-5 when the L5-S1 disc displayed a healthy appearance on magnetic resonance imaging. He recommended extension to the sacrum only in the cases of pre-existing pathology at L5-S1, such as spondylolisthesis and spinal stenosis, or significant sagittal imbalance that in turn is more likely to lead to subsequent disc degeneration at the L5-S1 level.^{28,40}

The distal fusion level should be at a neutral and stable vertebra and should never end at a segment with a rotated spinal segment. The subadjacent segment should have little or no disc or facet degeneration. The first sacral level must be included in the distal fusion to achieve balance if there is an oblique takeoff of L5 on the sacrum with a fractional curve $>15^\circ$, a spondylolisthesis, or stenosis at the L5-S1 level.⁷

To summarize, the fusion level should not stop at a segment with a rotated spinal segment in order to avoid aggravating further subluxation in the postoperative period. In addition, to prevent issues in the adjacent segment, it is recommended that a surgeon not stop a fusion at the apex of the deformity in either the coronal or sagittal plane.²⁹ Furthermore, the thoracic physiologic kyphotic apex must be avoided as an endpoint for instrumentation as caudal instrumentation can act as a moment arm that can lead to further progression of deformity.³⁰ Finally, the surgeon should avoid ending instrumentation at a segment with posterior column deficiency or listhesis in any direction.

In general, most patients with ALDS do not require an osteotomy. Posterior lumbar interbody fusion (PLIF) and transforaminal lumbar interbody fusion (TLIF) can have a positive effect on restoring sagittal and coronal balance owing to a combination of an anterior release and the support of an intervertebral graft.²⁹ If the stiffness of the deformity is such that it cannot be corrected by an anterior release and posterior instrumentation, then partial resection of the inferior articular processes may be required. In more severe cases, spinal osteotomies such as a pedicle subtraction osteotomy or Smith-Petersen osteotomy aid clinical realignment and subsequently decrease the stresses seen at the instrumentation-bone interface.

SURGICAL TECHNIQUE

For the treatment of adult spinal deformities, the available approaches include anterior-only, posterior-only, and combined anterior and posterior surgery. Minimally invasive techniques and nonfusion techniques have also been discussed.

Anterior-only Approach

Anterior lumbar interbody fusion (ALIF) has been shown as a reliable technique in the treatment of adult spinal deformity. Studies have shown that an anterior release with structural anterior column support may provide several benefits, including improved stability, decreased stress on spinal implants, improved fusion rates, better correction of lumbar lordosis, and consequently a direct reduction in the number of fusion levels necessary. The thorough release of contracted tissues and osteophytes, preparation of the interbody space, and placement of structural anterior column support is more directly achieved from an anterior approach.³¹⁻³³

Only a few relatively young adult patients with ALDS ultimately undergo an anterior-only approach. Pain from the anterior incision, incisional hernia, ileus, abdominal adhesions and strictures, large vessel injury, and other complications have been associated with the anterior approach.³⁴ The anterior only technique is not typically used in older osteoporotic patients secondary to the increased risk of catastrophic anterior instrumentation failure. An ALIF is therefore usually combined with a posterior instrumented correction and fusion. Various studies, however, have found that deformity correction is not consistently improved with the addition of anterior surgery in degenerative lumbar scoliosis.^{33,35,36} Crandall et al.³⁵ compared

the clinical and radiographic outcomes in degenerative lumbar scoliosis patients treated with posterior-instrumented correction and fusion combined with ALIF to TLIF. They found that both ALIF and TLIF are effective in improving clinical and radiographic results in degenerative lumbar scoliosis patients. They also noted that deformity correction was similar (70%) between the two groups. Ultimately, the authors concluded that anterior surgery is not routinely required to treat all cases of degenerative lumbar scoliosis.

Posterior-only Approaches

Nowadays, more and more surgeons prefer to perform a posterior-only approach for ALDS patients. In general, most patients with lumbar degenerative scoliosis also have concomitant spinal stenosis secondary to degeneration, and thus, these patients often require a direct posterior decompression.^{31,32} Growing evidence suggests that a posterior-only approach may be as effective as combined anterior-posterior surgery for most cases.^{39,40} Aggressive decompression alone, however, may be a detriment to the stability of spine and result in curve progression.^{22,37} The use of posteriorly placed interbody grafts in deformity correction surgery has gained popularity as a means of providing anterior column structural stability, increased fusion rates, and restoring as well as preserving lumbar lordosis.^{31,36,38} Biomechanical analysis has demonstrated that the use of TLIF grafts and bilateral pedicle screws allow deformity correction with restoration of the mechanical stiffness of spine 10–20% greater than that of non-instrumented specimens.⁴¹ Despite minor biomechanical differences between TLIF and ALIF stiffness, both procedures significantly enhance segmental stability with good clinical results.^{35,36,42}

Special Surgical Technique

Less Invasive Surgical Correction

Traditionally, the interbody fusion graft is placed through either an anterior (ALIF) or posterior (PLIF or TLIF) approach. Posterior approaches (PLIF and TLIF) place the nerve roots and thecal sac at greater risk during graft insertion because these structures must necessarily be exposed, and then protected. With the advance of surgical technique, more and more procedures like these may be performed by minimally invasive means. Minimally invasive surgery is still in its relative infancy and the majority

of the touted advantages are somewhat theoretical at this point and not clearly supported in the literature. The proposed advantages include decreased blood loss, shorter operating time, less postoperative pain, lower risk to the neural elements, shorter hospital stay, and faster return to activities. This “evidence” has supported the growing usage of minimally invasive techniques in spine surgery.

Among spinal deformity surgeries, adult deformity corrective procedures carry a higher complication rate, because this group often has multiple comorbidities.^{43,44} For ALDS patients, minimally invasive surgery may include posterior multilevel percutaneous pedicle instrumentation and one or a combination of the following interbody disc release and fusion procedures: Lateral interbody fusion and axial lumbar interbody fusion (AxiaLIF). The lateral approach provides an alternative to traditional interbody approaches, which uses a corridor that is designed to protect the vital structures both anteriorly and posteriorly to the vertebral body. With the lateral approach, access to the spine from the T-7 level down to the L4-5 level is possible. However, the L4-5 level is often difficult to reach due to a high riding iliac crest. The means to access the L5-S1 laterally has not been developed.^{45,46}

For ALDS patients, the proposed advantages of minimally invasive surgery make it a promising technique. In comparison to the more familiar posterior approach, minimally invasive lateral access to the spine is a relatively technically demanding method with a steep learning curve.

Nonfusion Technique

In elderly patients, the type of surgery chosen should be the least aggressive possible, and the length of the surgical procedure should be considered very carefully.⁴⁷ The surgical treatment of ALDS with spinal arthrodesis in addition to decompression of neural elements may require a lengthy surgery with excessive intraoperative blood loss. Operative time appears to be the most significant risk factor for early perioperative complications.⁴⁸ As alternatives to spinal arthrodesis, nonfusion-instrumented techniques such as pedicle-based dynamic instrumentation systems and soft stabilization devices have been used for the treatment of degenerative diseases. Some authors have presented promising results using the Dynesys system in the treatment of degenerative spondylolisthesis.^{49,50} Silvestre et al.⁵¹ performed nonfusion techniques after a decompressive laminectomy with the dynamic stabilization (Dynesys) system in 29 elderly patients with degenerative lumbar scoliosis. Radiographic evaluation at follow-up

revealed that the dynamic fixation system provided substantial stability. It prevented further scoliosis progression and spondylolisthesis after wide laminectomy. However, not every author has reported satisfactory results with these implants.⁵² Kanayama et al.⁵³ concluded that spinal “ligamentoplasty” cannot completely replace spinal fusion. More studies are needed to validate its use in this degenerative pathology.

RESULTS AND COMPLICATIONS

Due to the technical complexity, extensive need for spinal reconstruction and confounding patient comorbidities; surgery for adult degenerative scoliosis is associated with a relatively high rate of complications. In the overwhelming majority of cases the age of the patient is the primary risk factor for perioperative complications. This was demonstrated in a large series by Pedro Berjano et al., where the frequency of complications was directly related to the patient's age. The incidence of major complications and overall complication incidence rate was 6% and 17%, respectively, in the 25–44 age group, 15% and 42%, respectively, in the 45–64 age group, and 29% and 71%, respectively, in the >65 age group.

Clinical Results

Despite being fraught with potential complications in general, the clinical improvement of ALDS patients undergoing surgical correction is favorable. This is especially true in terms of overall pain visual analog scale (VAS) and ODI when compared to that of their preoperative status.³⁵ Interestingly, the mean ODI has not shown to significantly differ among patients who have experienced early complications with those who have not. This outcome may just be a factor of the relatively benign nature of the vast majority of early complications. In contrast, patients suffering from late complications display significant worsening of their ODI from baseline relative to those patients who did not experience late complications.

A major factor negatively affecting clinical outcome is a resultant positive sagittal imbalance.⁴⁸ Studies have demonstrated that patients with a predominant back pain component who have failed to respond to non-operative treatment can typically expect a 50% improvement in pain and function with surgical intervention.¹⁰ On the other hand, patients with radiculopathy as their primary complaint usually note a 75% improvement in leg discomfort.^{55,56}

When neurologic claudication is the primary indication for surgery, postoperative SF-36 has demonstrated a statistically significant improvement in bodily pain, social function, emotional health, mental health, and mental composite. As would be expected, patients tended to be more satisfied with the outcome of surgery if their claudication was eliminated.²⁹ Two risk factors that account for a less than successful outcome are a sacrum to curve apex fusion (i.e. short segment fusion) and a positive sagittal imbalance after surgery.⁴ Of course the extent of surgical aggressiveness is an important factor that impacts the improvement of self-assessment survey results. Improved ODI scores have been routinely seen in decompression alone and decompression with limited fusion, but not in decompression with full curve fusion.⁴ A potential reason for this discrepancy is that decompression with full curve fusion is associated with an increase in intraoperative blood loss and hospital stay relative to decompression alone.⁴

Crandall et al.³⁵ found no statistical difference between the ALIF and TLIF groups in ODI, VAS, and pain medication use. The decline in use of pain medication after surgical treatment was nearly identical between the groups. Minimally invasive interbody fusion has also been shown to improve the self-assessment survey results. TorMenti et al.⁵⁷ found that patients who underwent combined extreme lateral interbody fusion and posterior instrumentation had VAS scores that dramatically decreased when comparing preoperative (mean 8.8) to postoperative values (mean 3.5).

Radiographic Results

As mentioned before, the use of interbody grafts in deformity correction surgery may help to restore and preserve the alignment of the lumbar spine. The percent of coronal curve correction is about 70% in ALIF and TLIF patients and the difference between the two groups does not appear to reach statistical significance. The correction of the deformity, however, is not the primary goal of surgery for patients undergoing decompression only or decompression with limited fusion. Consequently, radiographic measurements of the main lumbar curve, lumbosacral curve and lumbar lordosis exist unchanged pre- and postoperatively in these patients. In contradistinction, these parameters are improved significantly when looking at patients who underwent full curve fusion, though the clinical benefit of such an extensive procedure is unclear.⁴

Complications

The spectrum of perioperative complications of ALDS can be divided into early and late complications:

- Early/perioperative complications
 - Neurologic deficit
 - Epidural hematoma
 - CSF leak
 - Wound infection
 - Urinary tract infection
 - Cardiopulmonary disease
 - Deep vein thrombosis
 - Ileus
- Late complications
 - Pseudarthrosis
 - Failure of instrumentation
 - Adjacent segment disease

Degenerative lumbar scoliosis is mostly seen in the elderly population who present with a myriad medical co-morbidities.¹² Among spinal deformity surgeries, adult deformity corrective procedures carry a high complication rate. Complications include urinary tract infection, wound infection, pseudarthrosis, hardware failure, durotomy, myocardial infarction, neurologic injury, adjacent segment degeneration, blindness, and death.^{14,43,44,54,60-62} Published potential complications for the operative treatment of adult degenerative scoliosis span the entire spectrum of severity, and vary depending on the type of operation, chosen surgical approach, and the presence or absence of instrumentation.

Cho et al.⁴⁸ reported that 14 of 49 patients developed early complications and 18 developed late complications in one small surgical study of patients with degenerative scoliosis. In a larger study, the authors reported 643 patients who underwent a posterior-only approach for degenerative scoliosis.⁴⁰ They reported only a 9% reoperation rate for pseudarthrosis (3.7%), curve progression (2.0%), infection (1.4%), and prominent instrumentation (0.6%) after a 4-year follow-up period. The incidence of complications in other series ranged from 20% to 80%.^{28,58} With advances in neurophysiologic monitoring, and improvements in perioperative management, these risks have decreased significantly.⁴³ Numerous factors are attributed to the development of complications including, but not limited to, motion segment stiffness, osteoporosis, stenosis, spondylolisthesis, rotation, instability, spinal imbalance, and medical comorbidities.^{48,59}

Early perioperative complications usually are operation or approach-related complications. One of the most

significant operative complication is excessive intraoperative blood loss, directly related to the number of levels fused.⁵⁸ Different approaches are also associated with different complications. For example, the anterior approach is associated with complications that include vascular injury, ileus, and retrograde ejaculation.⁶³ Approach-related complications of the lateral minimally invasive approach include bowel or other abdominal viscera injury, numbness, dysesthesia, and pain in the groin and lateral thigh and psoas weakness.⁴⁶

Late complications are often instrumentation related and consist of pseudarthrosis, adjacent segment disease, and implant failure among others. Fusion extending to the sacrum entails a larger operation with an increased rate of pseudarthrosis at the lumbosacral junction.⁶⁴ Kim et al.⁶¹ found an overall pseudarthrosis rate of 24%, with nearly half of those patients developing pseudarthroses at L5–S1. Risk factors for the development of pseudarthrosis include a thoracolumbar kyphosis, hip osteoarthritis, positive sagittal balance >5 cm, age >55 years, and incomplete sacropelvic fixation.^{13,61}

There is a tendency for increased adjacent segment disease following short-segment fusion compared to long-segment fusion. Cho's et al.²⁹ found that proximal adjacent segment disease was seen in all cases with short segment fusion. On the contrary, in long segment fusions, there were only two cases of proximal adjacent segment disease and three cases of distal adjacent segment disease. Despite the presence of high complication rates and difficult decision making, the clinical outcomes appear to support such risks in appropriately selected patients.¹⁹ As mentioned previously, these procedures must require careful planning and patient education to decrease the complication rate and to manage the patient's expectations.

POSTOPERATIVE MANAGEMENT

One or more antibiotics should be administered for at least 24 hours postoperatively to prevent a surgical site infection. Nutritional supplementation should be considered until patients are able to consume enough calories independently, typically occurring by the second or third postoperative day. Postoperative pain management in the immediate postoperative period is very important to expedite functional rehabilitation. This may present a challenge for patients with long-term narcotic usage. If possible, patient-controlled analgesia should be used in these patients. Due to the adverse effect on fusion rates,

nonsteroidal anti-inflammatory drugs are not recommended in fusion patients. All patients should be given full-length antiembolic compression stockings. A Vena cava filter before surgery may be considered for high-risk patients or patients with known history of deep vein thrombosis who have contraindications to blood-thinner usage.

Patients are encouraged to walk with a fitted custom thoracolumbosacral orthosis as soon as all wound drains are removed, which typically occurs by the second or third postoperative day. Patients are instructed to wear the orthosis whenever they are out of bed for at least 3 months. Full-length radiographs are taken at 3 months, 6 months, 1 year, and 2 years follow-up.

SUMMARY

Patients with ALDS may develop significant symptoms of low back pain, leg pain, and spinal imbalance. The goals of surgical treatment include relief of leg and back pain, and the correction of deformity. Transfeldt et al.⁴ noted that there are a myriad of factors to be considered when considering surgery. How much back pain is there compared to leg pain? If the primary purpose of the surgery is to relieve radiculopathy, will the patient be able to put up with their residual back pain? Would the patient prefer to have a smaller decompressive operation now and face the risk of a fusion later, or would they rather have a bigger surgery now with a less likelihood of more surgery later?

Several surgical options are available for degenerative lumbar scoliosis, including decompression alone, decompression with limited fusion within the deformity, and decompression with long segment instrumentation. However, these complex surgeries are accompanied by substantial complications mostly due to the advanced age of this patient population.¹² When considering the various complications, no statistically significant difference has been demonstrated between the ALIF and TLIF groups for rate of nonunion, adjacent fracture, adjacent level disease, infection, or other complications. The advent of minimally invasive decompression techniques has so far not led to improved outcomes for patients with lumbar deformities who wish to avoid spinal fusion.

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Osteotomy Techniques for Coronal and Sagittal Plane Thoracolumbar Deformities

Noriaki Kawakami, Melvin D Helgeson

Snapshot

» Types of Osteotomies

» Application of Osteotomy Procedures and Bone Union

INTRODUCTION

The goal of surgical treatment for spinal deformity is to correct the deformity and to stop the progression of abnormal spinal curvature. However, it is sometimes difficult to achieve a straight spinal column in the coronal aspect and a physiological curvature in the sagittal aspect. This can be due to overlooked disadvantages such as the loss of mobile segments from the spinal fusion and possible surgical complications from the correction of the spinal deformity. Surgeons should consider how many mobile segments must be sacrificed for adequate correction and fusion in the spinal column and attempt to fuse the shortest segment possible, with minimal complications. Occasionally, secondary curvatures (nonstructural) can be spontaneously corrected with the improved spinal balance from the correction of the main curve. However, some secondary curves may not be corrected, leading to deterioration of the spinal balance; a consequence of the correction of the main curve.

Abnormal spinal balance can cause not only progression of the residual curvatures but also reduced quality of life due to back pain, lower extremity pain, and neurological symptoms during long-term follow-up period.^{1,2} Therefore, the ultimate goal in the surgical treatment of spinal deformity is the maintenance and acquisition of not only coronal but also sagittal spinal balance with the fewest fusion segments. In some patients, surgeons may need to correct very rigid curvatures in order to achieve these goals.

The types, characteristics, and magnitude of spinal deformities vary between patients. The types of curvature

in congenital scoliosis or kyphosis may be more angular with greater rigidity. Other deformities in adult scoliosis or kyphoscoliosis may be sagittally or coronally off-balance due to degenerative changes in the lower lumbar segments. Although spinal instrumentation has progressed with increasing potential for correction, those patients with high angular rigidity and/or “take-off” in coronal or sagittal balance frequently need vertebral osteotomies for the correction of these curvatures. This chapter will describe the techniques and indications of various types of vertebral osteotomies for thoracolumbar deformities. Intraoperative spinal cord monitoring (especially motor-evoked potentials) is required in all osteotomy procedures described in this chapter as a necessary antecedent or precondition to prevent spinal cord-related neurologic complications. However, perioperative surgical complications are described in a different chapter.

TYPES OF OSTEOTOMIES

Although many spinal surgeons have introduced various types of vertebral osteotomies,³⁻⁹ they can be mainly categorized into three types: posterior chevron-shaped osteotomy, wedged-osteotomy including posterior subtraction osteotomy, and vertebral column resection (VCR).

Posterior Chevron-Shaped Osteotomy

The posterior wedged-shaped osteotomy, chevron manner, was first introduced by Smith-Petersen, et al.⁴ in 1945.

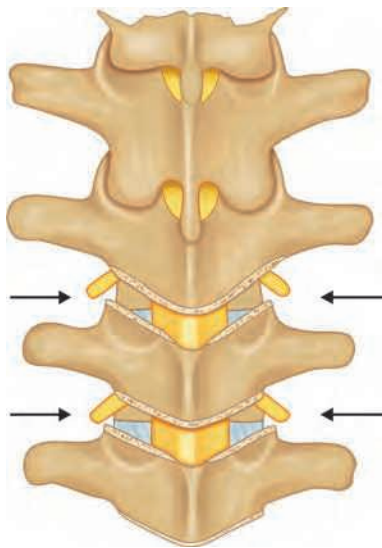


Fig. 115.1: Chevron-shaped osteotomy (Smith-Petersen osteotomy, Ponte osteotomy). Resection of bilateral superior and inferior facet joints in a chevron fashion (arrows).

It was initially employed to correct kyphosis caused by ankylosing spondylitis using this method. Several surgeons have attempted this type of osteotomy with a combined anterior and posterior approach for the iatrogenic flat back due to previous fusion,¹⁰⁻¹⁴ multiple applications for Scheuermann disease,⁴ as well as kyphosis due to ankylosing spondylitis.^{14,15} Multiple applications of *posterior chevron-shaped osteotomies* for Scheuermann diseases were first introduced by Ponte, et al. in 1984.⁹ Smith-Petersen osteotomy (SPO) and Ponte osteotomy are frequently confused and interchangeably described, although originally SPO was designed to be performed at only one segment while Ponte osteotomy is designed for multiple segments. This chapter treats both types of osteotomy as “chevron-shaped osteotomies” because they apply a similar surgical technique and procedure in terms of anatomical aspects in spite of the difference in the number of segments that are osteotomized.

Surgical Planning and Technique

This type of osteotomy may be performed with combined anterior and posterior approaches or through only a posterior approach. The chevron-shaped osteotomy is actually only performed for posterior structures, regardless of which approach is chosen. Preoperative evaluation and construction of a valid strategy for the correction of the spinal deformity are very important and surgeons should decide which and how many intervertebral segments

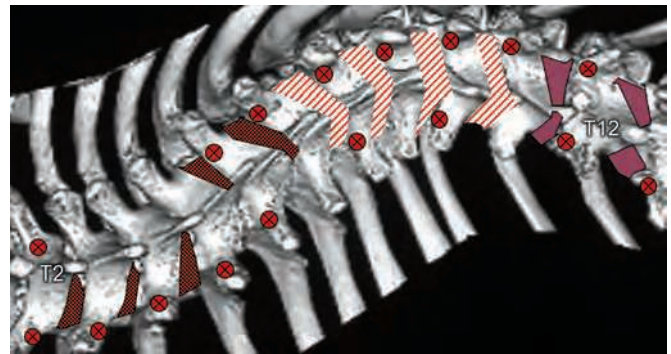
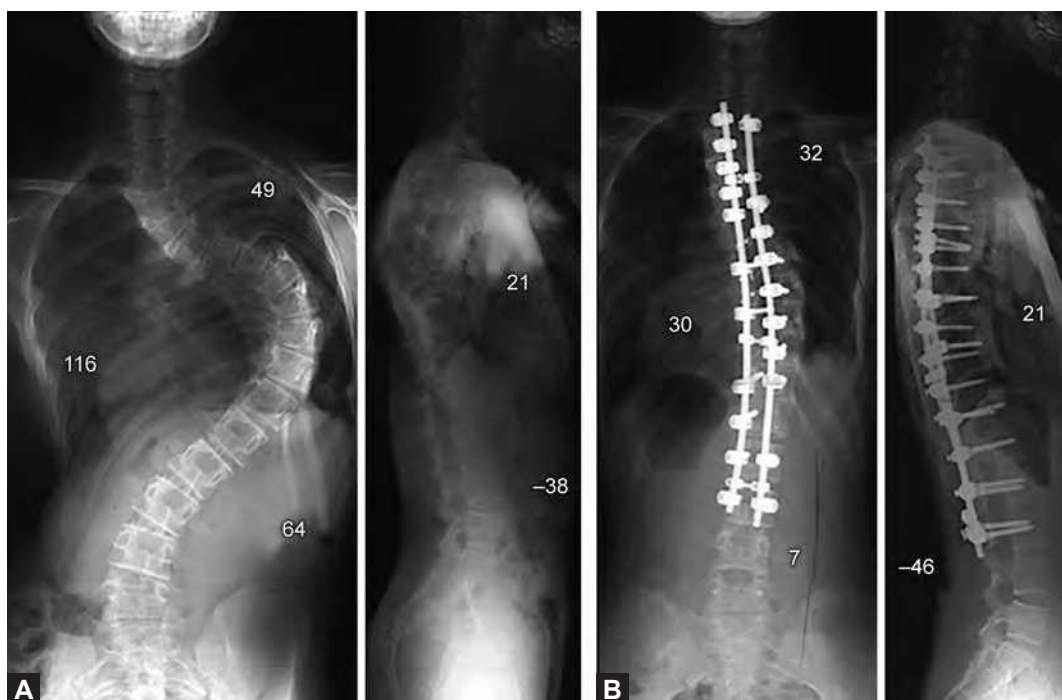


Fig. 115.2: Asymmetrical chevron-shaped osteotomy. Multiple asymmetrical chevron-type osteotomies were planned on the periapical segments from T7 to T12 for correction of severe scoliosis.

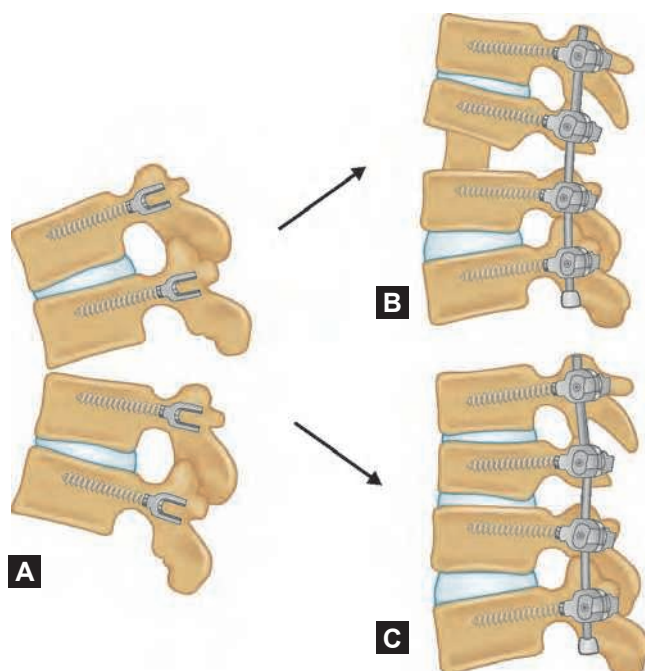
must be osteotomized to obtain the maximum correction of either scoliosis and/or kyphosis. Obtaining 5–10° per segment is the approximate goal for chevron-shaped osteotomy and surgeons must estimate the amount of correction of the spinal curvature required to achieve ideal coronal and sagittal balance by determining how many segments to be osteotomized in a chevron fashion.¹⁶

Initially, the bilateral inferior facets are completely resected using a rongeur or an osteotome followed by resection of the superior facets by using a Kerrison rongeur. The roots usually run medioinferior to the pedicle from the medial to lateral region. Surgeons will be required to carefully dissect the roots from the surrounding tissues. The key here is to expose the roots completely, up to the far lateral site by releasing even the intertransverse ligaments to prevent root impingement at the time of correction, which is achieved by closing the osteotomized gap (Fig. 115.1). Chevron-type osteotomy should be asymmetrically performed in patients with severe scoliosis or kyphoscoliosis, for correction of scoliosis (Figs. 115.2 and 115.3).

Typical SPO or Ponte osteotomy was originally established as a posterior closing osteotomy without any anterior release.^{4,9} The anterior longitudinal ligament acts as a hinge in SPO or Ponte osteotomy to correct kyphosis. These types of posterior chevron osteotomies may be appropriate for sagittal imbalance or kyphosis, but not for coronal deformity.¹⁷ Some surgeons modify the SPO or Ponte osteotomies through a combined anterior release and posterior approach, thus causing an anterior opening posterior closing osteotomy with the posterior longitudinal ligament acting as a hinge, or through a posterior only approach by placement of a strut bone graft or a cage as a focus for center of rotation¹⁸ (Figs. 115.4A to C).



Figs. 115.3A and B: Correction of scoliosis using multiple chevron-shaped osteotomies. Case: A 10-year-old female with early onset scoliosis. Scoliosis was corrected from 116° to 30° using multiple chevron-shaped osteotomies from T7 to T12.



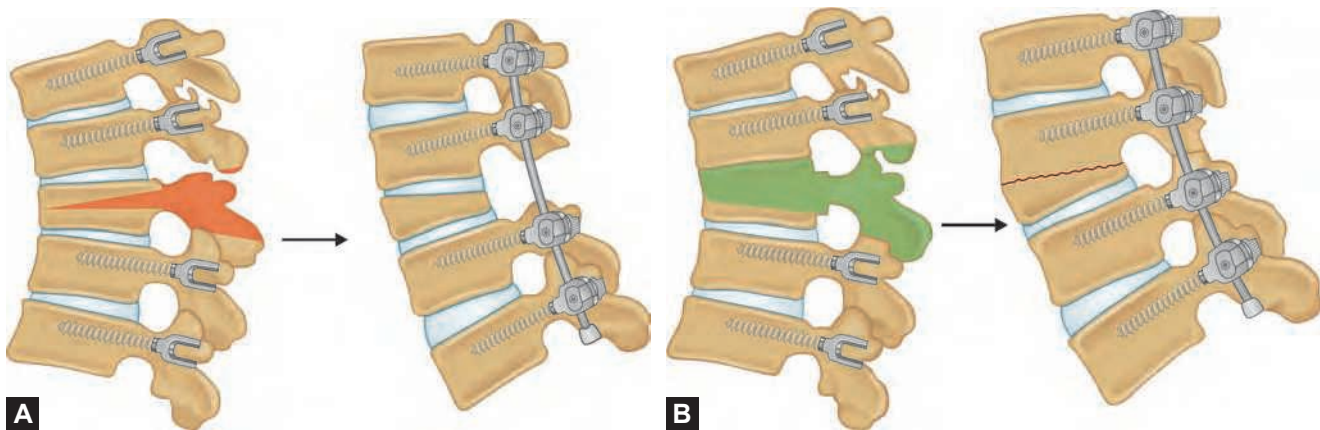
Figs. 115.4A to C: Modification of chevron-type osteotomy. Local kyphosis (A) can be corrected using chevron-shaped osteotomy. Anterior release combined chevron-shaped osteotomy with a strut bone into the gap (B) can correct kyphosis much better than simple chevron-shaped osteotomy (C).

Wedge-Osteotomy

Wedge-osteotomy can be simply summarized as a wedge-shaped resection of both anterior and posterior structures on the vertebral column for the correction of three-dimensional deformities. There are two types of wedge-osteotomy based on the location of osteotomy on the vertebra: intravertebral and intervertebral. The former is an osteotomy performed inside of a single vertebra; including pedicle subtraction osteotomy (Posterior Three-Column Wedge-Resection, PSO).^{3,19-26} Transpedicular decancellation osteotomy (TDO) also belongs to this group.^{6,27-30} Pedicle subtraction osteotomy and TDO are almost the same procedure in terms of the approach through pedicles with the addition of wedged-shape resection of the lateral wall and posterior cortex of vertebral body in PSO (Figs. 115.5A and B).

Pedicle Subtraction Osteotomy

Thomasen³ first presented posterior traspedicular subtraction osteotomy for correction of kyphosis in patients with ankylosing spondylitis. This procedure is a three-column osteotomy with a wedge-shaped osteotomy inside one vertebra through a posterior approach.



Figs. 115.5A and B: Intravertebral posterior three-column wedge-resection. (A) Transpedicular decancellation osteotomy. (B) Pedicle subtraction osteotomy (posterior three-column wedge-resection).

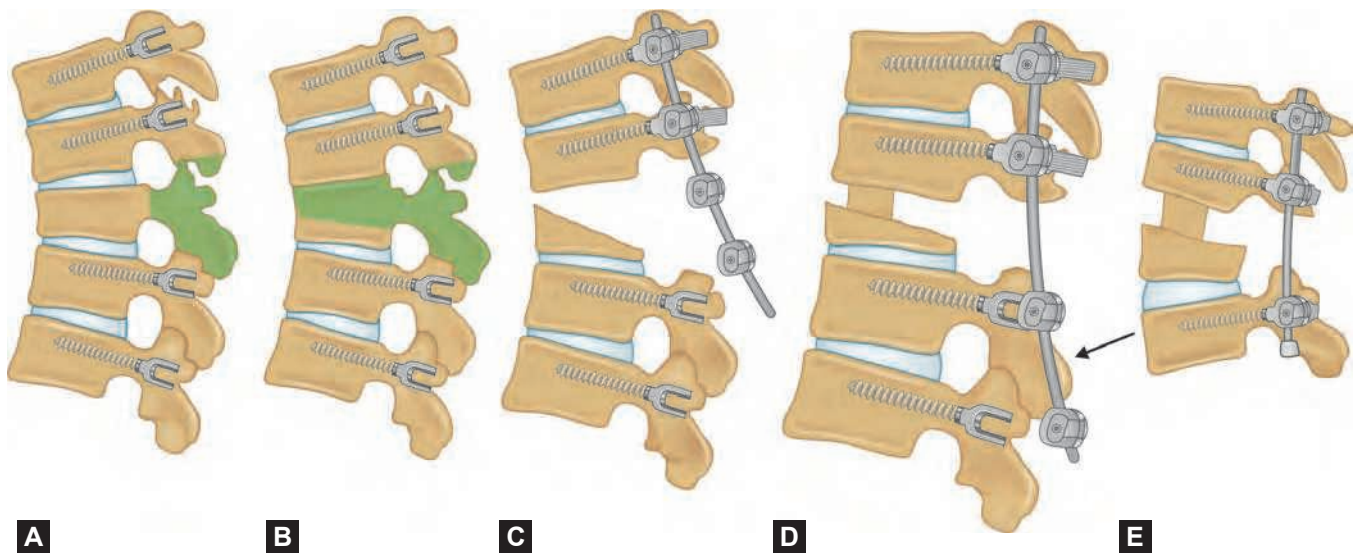
Surgical Planning and Technique of PSO

The site of osteotomy is at the apex of the kyphosis if possible and it may be located at L2, L3, or L4 in most patients with degenerative adult lumbar kyphoscoliosis. Preoperative evaluation of parameters related to the coronal and sagittal alignment, such as flexibility of main and adjacent curves, L4 tilting angle, pelvic tilt, and pelvic incidence, is important for determining operative strategies of spinal deformities.¹⁶ Several surgeons have attempted to predict restoration of sagittal alignment after vertebral osteotomies and correction/fusion using mathematical formulas.³¹⁻³³ Most of these formulas, however, are known to be unreliable at best to predict sagittal vertical axis after vertebral osteotomies because of the influence of pelvic parameters and secondary changes of unfused curves; factors that are difficult to predict after the correction of main curves.³⁴

For procedures that destabilize the spine, pedicle screws should be inserted first. Prior to performing a PSO, pedicle screws should be inserted at least two vertebrae cranially and caudally from the target vertebra (at least four screws above and below). Fusion may be extended beyond the deformed vertebrae if old compression fractures are recognized at locations adjacent to the upper end or lower end of the instrumented vertebrae (UIV, LIV). Magnetic resonance imaging may give us useful information related to the determination of UIV or LIV.

The area of osteotomy is outlined followed by laminectomy with complete bilateral facet removal. The dural sac and the bilateral roots that run medially along the pedicle are exposed. The bilateral pedicles of the vertebra for PSO

are isolated from the surrounding tissues, first medially, then caudally, cranially, and finally, their lateral walls are exposed by resecting the transverse processes and/or the medial side of the ribs up to the tip of rib heads. The lateral wall of the vertebral body is subperiosteally exposed, and the vertebral body is removed piece by piece, through a transpedicular approach. The removal of the lateral cortex of the vertebral body should be done in a wedge-shaped fashion without damaging the periosteum. The medial wall of the pedicles can be used to protect the neural tissues during this procedure. The removal of the medial wall of the pedicles should be done after removing some of the bone from the vertebral body because the medial wall of the pedicles can be a barrier during procedures in terms of prevention of neural damage and bleeding from epidural vessels. The vertebral cortex under the dural sac should be removed after cauterization of both the epidural vessels and the longitudinal ligament at the same time. It is very dangerous to retract the dural sac at the time of removal of the dorsal cortex of the vertebral body, particularly in the thoracic area. The L-shaped bone impactor or a curette may be useful for removal of this portion. The key is to control the bleeding from the epidural vessels or basivertebral vessels during removal. A rod may have to be temporarily placed before the posterior wall of the vertebral body is removed in order to stabilize the vertebral column, preventing the gap from decreasing or displacing the cranial vertebral column from the caudal one. Correction is thus achieved by closing the osteotomized gap and using the anterior cortex as a hinge during a compression maneuver. Extra precautions must be taken to prevent the impingement of the roots and dural invagination at the



Figs. 115.6A to E: Intervertebral posterior three-column wedge-resection (extended pedicle subtraction osteotomy). (A) Laminectomy and facetectomy. (B) Pediclectomy and transpedicular wedge resection of the vertebral body. (C) Placement of the rod. (D) Strut bone graft into the gap as a furculum followed by correction of kyphosis using cantilever maneuver. (E) Correction of kyphosis by using compression maneuver with a furculum of the strut bone placed in the vertebrectomized gap.

edge of the laminae. Bridewell^{22,23} reported partial removal of laminae at the center of the spinal canal in order to check whether the neural tissues are impinged. All lamina are routinely removed to securely check that both the dural sac and nerve roots are free from compression while closing the wedge-shaped defect to correct the kyphosis. The defect between the cranial and caudal laminae should be grafted with local autograft bone to ensure bony union.

Intervertebral Wedge Osteotomy

Intervertebral wedge resection is a type of osteotomy beyond the endplates and into intervertebral discs cranial and/or caudal to the vertebra, and is commonly combined with PSO. If greater correction of kyphosis is required, resection of the disc cranial to the osteotomized vertebra in addition to the PSO procedure may be done to obtain a greater correction angle (Figs. 115.6A to E). This may be called an “extended pedicle subtraction osteotomy (EPSO)” (Figs. 115.7A to C).

Intervertebral wedge osteotomy through an anterior and posterior combined approach may be useful for the correction of hyperlordosis of the lumbar spine or segmentation failure of congenital scoliosis. Lewis et al.³⁵ reported anterior vertebral wedge osteotomy with resection of disc tissue combined with a posterior SPO for the correction of a fixed lumbar hyperlordosis. However, they failed to correct hyperlordosis using simple posterior distraction

because the anterior osteotomized gap also opened at the same time. Consequently, they achieved correction of hyperlordosis through posterior reduction to an under-contoured rod. They named this procedure “Reverse Smith-Petersen Osteotomy (RSPO)”. Wang et al.³⁶ presented the case of one patient with arthrogryposis exhibiting severe hyperlordosis that was corrected by bending the operating table after anterior wedge osteotomy and posterior SPO. Correction of a fixed lumbar hyperlordosis requires a combined anterior wedge resection and posterior SPO followed by an anterior shortening and posterior lengthening procedure.

Segmentation failure in congenital scoliosis may be another proper candidate for combined anterior wedge osteotomy and posterior asymmetrical chevron-shaped osteotomy. These deformities often include anomalies in multiple segments. It is much safer and easier to perform intervertebral release and wedge resection of the anomalous vertebral segments both cranially and caudally in order to change wedged vertebral bodies into a rectangular shape through the anterior approach. In addition, scoliosis can be corrected from the posterior approach by a compression maneuver on the convex side and distraction on the concave side simultaneously after performing SPOs at the same segments. Wedge osteotomies can be applied with some modification for a variety of curvatures and spinal pathologies.



Figs. 115.7A to C: Pedicle subtraction osteotomy. Case: A 72-year-old woman with degenerative scoliosis with fixed sagittal imbalance. (A and B) Two-staged combined anterior and posterior procedure was planned. *First stage:* Combined anterior release with bone graft and posterior Smith-Petersen osteotomies from T12 to L3 was performed by rotational correction using segmental pedicle screw fixation. *Second stage:* Posterior correction and fusion with extended pedicle subtraction osteotomy on L4 was performed using intrasacral fixation. (C) Thoracolumbar scoliosis was corrected from 53° to 25°. Sagittal fixed imbalance was corrected to a well-balanced spinal curvature with lumbar lordosis of 52°.

Vertebral Column Resection

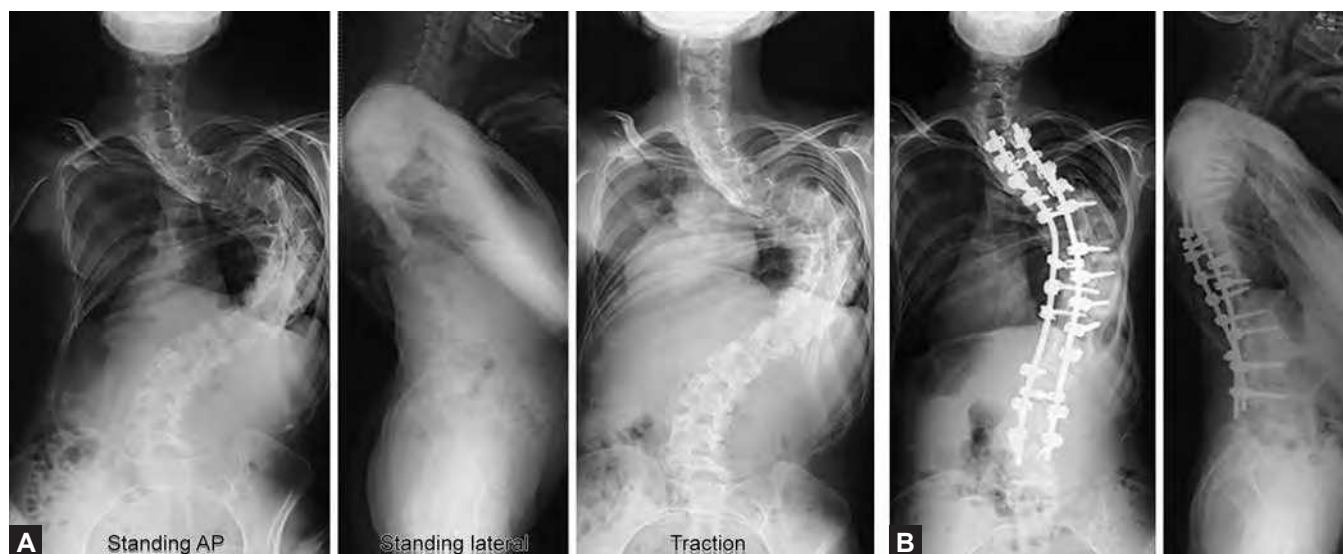
The resection of an apical vertebra for the correction of spinal deformity was the first described by MaLennan.³⁷ He has reported posterior resection and correction of the curvature using a postoperative cast. Several surgeons have reported their own modifications for the treatment of congenital spinal deformity, spinal bone tumor, spondylosis, etc.³⁸⁻⁴¹ However, all procedures for the resection of the VCR were through combined anterior and posterior approaches. Suk first introduced posterior VCR (PVCR) for the treatment of severe spinal deformities in 2002.⁸ Since then, several surgeons have attempted to perform posterior VCR (PVCR) for the correction of rigid angular spinal deformities.⁴²⁻⁴⁸ Several approaches can be modified and selected for posterior resection of the vertebral column. A pure PVCR, PVCR followed by a staged anterior procedure for an anterior column support, or one-staged or two-staged anterior and posterior combined VCR may be chosen based mainly on the experience of the surgeons or the special features of the spinal deformities.

Vertebral column resection is regarded as the most powerful procedure for obtaining the best correction of even the most rigid spinal deformities in all osteotomy procedures. Vertebral column resection may be indicated for angular rigid kyphosis or severe scoliosis >100–120° (with flexibility <25–30%) as other osteotomies methods

are insufficient in correcting such spinal curvatures (Figs. 115.8A and B). The most common indications for VCR are congenital rigid spinal deformities. Among these, hemivertebrectomy has been widely accepted as the standard procedure for surgical treatment even in the very young pediatric patients,⁴⁹⁻⁵¹ although this may not be regarded as a pure VCR because it is a unilateral VCR, not bilateral.

Surgical Technique for VCR

As described already, VCR can be performed through either a combined anterior and posterior approach or a posterior only approach. One of the reasons combined anterior and posterior approach may be chosen is that the surgeon may have limited experience with PVCR. In addition, a curve may benefit from a circumferential release due to the periapical rigidity to obtain better correction. It is usually very difficult to perform anterior release at the apical segments for severe scoliosis; thus, surgeons that choose anterior release and bone graft in the periapical regions may perform a double thoracotomy approach to access at least four or five intervertebral disc spaces. Two discrete thoracotomies are placed with preservation of at least two ribs between them for the stability of the chest cage. The rib heads should be resected, and internal thoracoplasty along the periapical convex of the thoracic cage may be added at the same time. This may be helpful for posterior exposure of the apical convex side.



Figs. 115.8A and B: Vertebral column resection for severe rigid scoliosis. Case: A 25-year-old woman with congenital scoliosis (mixed type) (A). Posterior vertebral column resection on T9 was performed with multiple Smith-Petersen osteotomies on several adjacent cranial and caudal segments. Scoliosis was corrected from 125° to 79° by cantilever and derotation maneuver (B).

The posterior approach may be performed with or without anterior release. Paravertebral muscles are dissected subperiosteally and exposure of the posterior structure should be thoroughly performed bilaterally to the tip of transverse processes. Exposure of the apical several laminae on the convex side is quite difficult in cases of severe angular scoliosis, due to the overlying ribs on the laminae. Screw insertion may be the next step followed by soft tissue release and bony release, including periapical multiple chevron-shaped osteotomies (SPO or Ponte). This decision is dependent on the rigidity/severity of the curvatures, or by the surgeon's preference. Screw insertion must proceed before osteotomies to stabilize curvatures during VCR procedures by placing temporary rods to prevent subluxation or angular translation. The recently developed computer guided system can be helpful for the accurate insertion of pedicle screws even into small apical pedicles on the concave side. Vertebral column resection is usually performed at the apex with multiple other posterior osteotomies (SPO or Ponte osteotomy) on the periapical and secondary curves if it is very rigid. SPO or Ponte osteotomies or partial facetectomies are planned preoperatively on every segment that should proceed before VCR. Vertebral column resection makes the spinal column dramatically unstable and performing other osteotomies may irritate or damage the neural tissues under these conditions.

Actual VCR procedures require laminectomies, bilateral facetectomies, and proximal rib resection (costo-transversectomy) using osteotomes, curettes, or Kerrison rongeurs at the level of the apical vertebrae. Ribs and spinous processes can be resected to use as strut grafts for the intervertebral defect or as bridging bones into the laminectomy gaps after correction. Careful exposure of the dural sac and nerve roots is extremely important. It may be necessary to ligate nerve roots at the proximal site in the thoracic spine to make a wider working space for resection of vertebral bodies in the thoracic spine. The pedicles can be isolated by resecting the surrounding bones and soft tissues. Pediculectomies on the concave side are particularly risky because the spinal cord rests very closely to the concave pedicle. The concave pedicles may become the cause of paralysis due to kinking of the spinal cord during VCR. The pedicles on the concave side may be thin and entirely cortical. Pedicles that are very hard and difficult to remove can be thinned by the use of high-speed bar to allow a much safer resection. Pediculectomies on the convex side are performed followed by subperiosteal exposure of the lateral wall of target vertebral body and resection. Thoracic nerve roots on the convex side may be also ligated to gain access for the remaining procedure. Cranial and caudal intervertebral disc tissues and cartilage are also removed to expose adjacent bony vertebral endplates. The posterior cortex of the vertebral body is the last part of resection. Meticulous bipolar cauterization of

epidural vessels for control of bleeding is essential and the longitudinal ligament is disconnected together with epidural vessels to free the dural sac from the vertebral body. The last structure of vertebral body can be mashed and removed by using curved impactors or special instruments designed for this procedure. It is very important to stabilize the spinal column during all these vertebral body resection procedures, by placing temporary rods (one or two) with at least two pedicle screws above and below in order to prevent subluxation or spontaneous closure of the osteotomy gap that may cause spinal cord irritation. Correction can be achieved by compression applied onto the temporary rod or the rod for fixation on the convex side. Shortening of the vertebral column can be too excessive causing the dural sac to sag onto the spinal cord, therefore an anterior structural cage should be placed to prevent this. Local bone graft (i.e. rib) or an appropriate size of cages should be placed to stabilize and to achieve solid fusion if the surgeon suspects that there will be space remaining in the anterior column. Temporary rods placed earlier are individually changed to permanent rods and compression is applied to stabilize the vertebral column after bone grafting (rib or spinous process) the laminectomy defect. Therefore, covering the dural sac as a bone bridge is helpful, not only to protect the spinal cord but also to facilitate bone fusion.

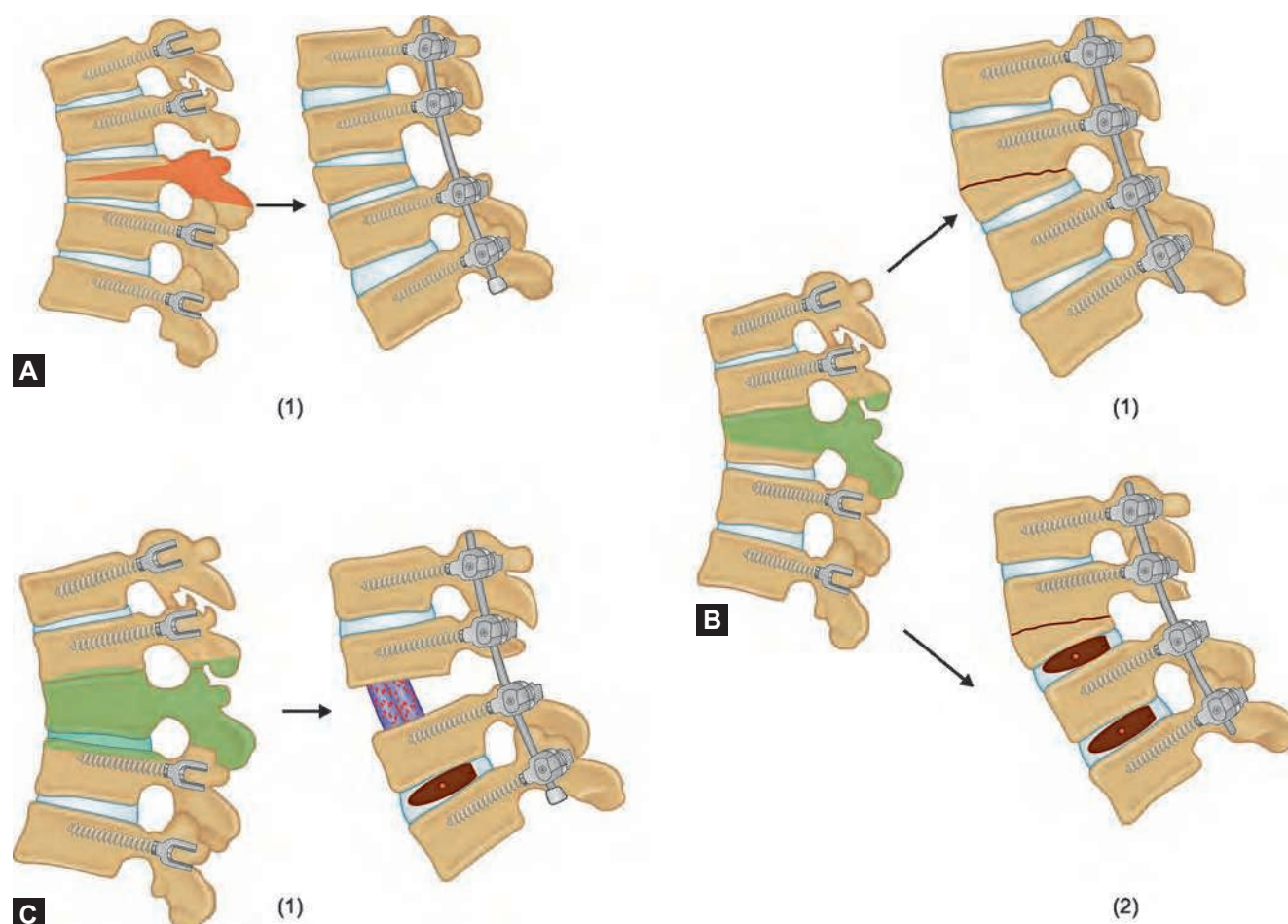
APPLICATION OF OSTEOTOMY PROCEDURES AND BONE UNION

Single or combined use of vertebral osteotomies dramatically increases the ability to correct severe spinal deformities. Recent reports of the surgical outcomes for severe spinal deformities describe their superiority in correction and clinical outcome.⁴⁵ These procedures change the strategic planning for treating not only severe rigid curvatures but also even for moderate scoliosis. This trend occurred due to the development of segmental pedicle screw fixation that provides strong correction and stabilization of the spinal column. However, the coupling of pedicle screw fixation and a combination of vertebral osteotomies can represent “a double edged sword.” In particular, an extensive osteotomy via a posterior approach can achieve much better correction, but it can destroy the bony continuity between adjacent vertebrae including facet joints and intervertebral discs. The short-term outcome has been reported to be excellent in terms of correction of rigid spinal deformity, due to the stabilizing force of pedicle screw fixation.^{44,-47,52,53} However, failure to achieve bone fusion

due to the unsatisfactory quality and quantity of grafted bone or malposition of grafted bone will lead to poor long-term outcome due to pseudarthrosis, screw loosening and/or back-out, rod breakage, and newly occurring neurological deficits. There have been few reports describing bone union in long-term follow-up studies. This is partly because pedicle screw fixation is strong enough to secure the spinal column, so that pseudarthrosis and screw loosening may be latent, or partly because it is very difficult to evaluate bone union in patients who underwent posterior fusion with spinal instrumentation using plain X-ray images. Smith et al.⁵⁴ reported that the rate of rod fracture in patients who underwent posterior instrumented fusion in adult scoliosis is 6.8%. They described that the rate of rod fracture is much higher (15.8%) after PSO. Surgeons should always pay attention to the location in reconstructed spinal column where bone union would take place if they decide to conduct vertebral osteotomies and bone graft (Figs. 115.9A to C).

KEY POINTS

- Vertebral osteotomies can be mainly categorized into three types: posterior chevron-shaped osteotomy, wedged-osteotomy including posterior subtraction osteotomy, and VCR.
- Preoperative evaluation and construction of a valid strategy for the correction of the spinal deformity are very important and surgeons should decide which type of osteotomies and how many segments must be osteotomized to obtain the maximum correction of either scoliosis and/or kyphosis.
- Obtaining 5–10° per one segment is the approximate goal for chevron-shaped osteotomy. Surgeons must understand its limitation of correction when they choose chevron-shaped osteotomy for the surgical treatment of spinal deformity.
- The key of posterior wedge osteotomies (including PSO, TDO, and VCR) is to control the bleeding from the epidural vessels or basivertebral vessels during removal of vertebral bodies
- Vertebral wedge osteotomies, in particular posterior VCR, are very challenging surgical procedures with a requirement of well-experienced surgeons and surgical teams. Surgeons must not only understand principles and surgical procedures of osteotomies but also obtain meticulous surgical skills when choosing vertebral osteotomies for the surgical treatment of severe spinal deformities.



Figs. 115.9A to C: The location of bone union and types of bone graft in vertebral osteotomies. (A) Intravertebral wedge osteotomy (TSO, TDO): (1) Autograft bone chips grafted into the osteotomized site. (B) Intervertebral wedge osteotomy (EPSO): (1) Autograft bone chips grafted into the osteotomized site; (2) posterior lumbar interbody fusion with cages. (C) Vertebral column resection: (1) Anterior column support with a mesh cage.

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- Posterior vertebral column resection is an effective alternative for moderate-to-severe deformities with limited flexibility although it is a technically demanding and exhausting procedure with possible risks or major complications.

A posterior-based VCR is a safe but challenging technique to treat severe primary or revision pediatric spinal deformities.

Smith JS, Shaffrey CI, Ames CP, et al. Assessment of symptomatic rod fracture after posterior instrumented fusion for adult spinal deformity. *Neurosurgery*. 2012;71: 862-8.

Early failure was most common after PSO and favored the PSO site, suggesting that RF may be caused by stress at the PSO site. Postoperative sagittal malalignment may increase the risk of RF.

Surgical Treatment of Spinal Deformities in the Setting of Osteoporosis

Tobias A Mattei, Carlos R Goulart, Daniel R Fassett

Snapshot

- » Epidemiology of Osteoporosis
- » Pathophysiology of Osteoporosis
- » Diagnosis of Osteoporosis
- » Medical Treatment of Osteoporosis
- » Complications of Deformity Surgery in Osteoporotic Patients
- » Salvage Techniques for Deformity Surgery in Osteoporotic Patients

INTRODUCTION

The bone quality of the spine plays an important role in the planning of surgical intervention for spinal deformities. Patients with osteoporosis may require surgical intervention including spinal instrumentation for several reasons, including severe mechanical pain due to sagittal or coronal imbalance, radicular pain or neurogenic claudication due to central canal or foraminal stenosis in the setting of adult degenerative scoliosis, and spinal instability or neurologic deterioration after a spinal trauma.¹ Although long spinal fusions in elderly patients is somewhat controversial, some studies have shown that elderly patients can obtain as much clinical benefit as their younger counterparts (≤ 55 years of age) after spinal deformity surgery.²

However, it has been shown that pedicle screw instrumentation of the osteoporotic spine carries an increased risk of surgical complications. Despite being the most rigid form of posterior instrumentation, pedicle screws may provide insufficient strength for rigid fixation and fusion in patients with osteoporosis. It has already been demonstrated that there is a positive correlation between bone mineral density (BMD) and the maximum torque required to insert a pedicle screw.³ A 5-year follow-up series of instrumentation in patients with osteoporosis demonstrated that the rates of pedicle fractures and compression

fractures may reach up to 13%, while progressive junctional kyphosis may occur in up to 26% of patients.⁴ These series also found an increased incidence of other late complications after spinal fusion in patients with osteoporosis, including pseudarthrosis with instrumentation failure, adjacent-level disc degeneration and progressive kyphosis.

Despite the strong evidence of the detrimental effects of poor bone quality in the postoperative outcomes of patients submitted to spinal instrumentation, it seems that the majority of the spine surgeons still fall short in performing an adequate preoperative evaluation of a patient's bone quality. For example, a questionnaire applied to spine surgeons attending a conference on disorders of the spine demonstrated that a large percentage of spine surgeons do not routinely screen for osteoporosis or osteomalacia before considering surgical intervention including spinal fusion.⁵

EPIDEMIOLOGY OF OSTEOPOROSIS

It has been estimated that osteoporosis currently affects more than 10 million people in the U.S. As the average age of the population increases, it is expected that a greater percentages of patients with spinal problems will be affected by this condition. Although osteoporosis is generally considered a disease of aging, other factors may significantly

influence the bone quality including mechanical issues (e.g. weight), physical activity, and nutrition (such as the overall intake of vitamin D and calcium), smoking, as well as medications (such as glucocorticoids and some hormonal treatments).^{6,7} Other secondary causes of osteoporosis are celiac disease, impaired renal function, diabetes mellitus, and renal tubular acidosis.⁷³

■ PATHOPHYSIOLOGY OF OSTEOPOROSIS

The most important factors related to bone quality are age and genetic factors, with many gene polymorphisms which affect bone mineral density having already been identified.^{8,9} Osteoporosis is characterized by loss of bone mass with deterioration of the general bone microarchitecture which occurs as a result of a dysfunction involving endocrine factors and their target cells in the bone. The two cells directly involved in bone homeostasis are the osteoclast, responsible for bone resorption, and the osteoblast, responsible two populations of cells for bone formation. Normally, these two populations of cells produce a stable equilibrium of bone formation and remodeling.^{8,10} If the activity of any of these cell populations become dysregulated, the final outcome may be osteoporosis.^{11,12}

In women, the bone mass reaches its peak around 25 years, while presenting an accelerated decline during the perimenopausal and postmenopausal period. It is also known that the rate of bone loss decreases yearly after the menopause, so that the slope of the curve depicting the decline in the bone mineral density (BMD) becomes less accentuated with progressing age. Conversely, it has already been shown that men present a slow and constant decline in BMD with aging without a faster decline in specific time points, such as the one which occurs in women in the perimenopausal period. It has been estimated that around the age of 60–65 both women and men will have equal rates of bone loss with the progressive decline leading to the lowest point for BMD values at the age of 80 years.^{7,13}

Aging, the greatest risk factor for osteoporosis, has been shown to lead to several changes in bone histology, including osteocyte death, increased bone turnover, thinned trabeculae, decreased cortical width, and increased cortical porosity.^{11,12,13} Another important etiological factor which must be taken into when evaluating a patient with osteoporosis is acute weight loss (either pathological—due to cancer, for example—or iatrogenic—after bariatric surgery).

The pathophysiology of such association between weight loss and bone mineral density has been shown to be multifactorial and to strongly correlate with the speed of weight lost. Decreased calcium, vitamin D, and protein intake during periods of caloric restriction have been shown to lead to decreased calcium absorption, increase in PTH, and increased bone resorption.⁷⁴

The main pathophysiological mechanism of osteoporosis in patients with diabetes mellitus is decreased bone formation, as insulin and IGF-1 have been demonstrated to have an anabolic effect on bone. Additionally, in vitro studies have also shown that sustained exposure to high glucose concentrations leads to osteoblast dysfunction, so that poor metabolic control may have a clear negative impact on bone mass.⁷⁵

The pathophysiology of steroid-induced osteoporosis include direct inhibition of osteoblast function, direct enhancement of bone resorption, inhibition of gastrointestinal absorption of calcium, increased urine loss of calcium and inhibition of sexual steroids.⁷⁶

■ DIAGNOSIS OF OSTEOPOROSIS

Osteoporosis can be defined as the presence of low bone mineral density with associated microarchitectural deterioration of the bone tissue, ultimately leading to bone fragility and increased risk of fractures. According to the World Health Organization (WHO) the diagnosis of osteoporosis should be based on BMD measurements obtained on dual energy X-ray absorptiometry (DEXA).¹⁴

Osteoporosis is defined as a BMD of 2.5 or more standard deviations below the peak bone mass for young healthy adults (T-score \leq 2.5). Regarding the investigation of osteoporosis, besides the DEXA scan, only a few laboratory tests are recommended including serum calcium, complete blood count, 25-Hydroxyvitamin D, T3, T4 and thyroid stimulating hormone (TSH). Serum electrophoresis should be considered for those patients with vertebral fractures in which the diagnosis of multiple myeloma is suspected.⁹

A DEXA scan should be obtained in any patient over 65 years of age or in younger patients with any of the following: Fragility fracture (a fracture involving mechanical forces that would not ordinarily cause a fracture in a healthy young adult), prolonged use of glucocorticoids, hypogonadism or premature (\leq 45 years) menopause, presence of any gastrointestinal malabsorption syndrome, primary hyperparathyroidism, parental history of hip

fracture, long-term smoking, high alcohol intake, low body weight or recent major weight loss, rheumatoid arthritis, incidental finding of a bone fracture or osteopenia in a recent X-ray, or the presence of any other comorbidity that may be associated with increased bone loss.^{9,13,15}

MEDICAL TREATMENT OF OSTEOPOROSIS

Calcium and Vitamin D

The main role of calcium and vitamin D supplementation in the management of osteoporosis is to prevent a further decrease in the BMD rather than any active role in new bone formation. Although there are some controversies about the effectiveness of calcium and vitamin D, a large recent meta-analysis published in “The Lancet” concluded that the benefit suggested by several studies in the literature, together with the associated low costs of such supplementation supports its general use for prevention of osteoporosis in patients beyond the age of 50 years. Regarding their influence upon the BMD, it has been shown that the best therapeutic effect can be achieved with daily doses of 1200 mg of calcium and 800 IU of vitamin D.¹⁶

Biphosphonates

The medical treatment with greatest impact for patients with osteoporosis consists in the use of biphosphonates. Biphosphonates are drugs which inhibit osteoclast activity by binding to the hydroxyapatite present in the bone. There are several drugs in this class, with the two most popular ones being Alendronate and Risedronate.¹⁷ Biphosphonates are well-known for their gastrointestinal side effects that may decrease compliance, such as vomiting, diarrhea, gastritis, nausea, inflammation and ulcers.^{18,19}

Despite the fact that early experimental models have suggested that biphosphonates might inhibit spinal fusion,^{77,79} recent studies in animals with osteoporosis have demonstrated that alendronate, in fact, increased the radiologic and histologic surrogate markers of spinal fusion, with increased final biomechanical strength and new bone formation.⁷⁸

In relation to clinical studies, a recent prospective randomized trial which employed a protocol of initiating alendronate right after the surgical procedure (35 mg/week) versus a control group in which only vitamin D (alfacalcidol—1 µg/day) was used, found that bridging bone formation was more frequently observed in the alen-

dronate group at all postoperative assessment periods. Additionally at 1-year postoperative follow-up, a solid fusion was achieved in 95% of the patients in the alendronate group versus 65% of those in the control group. Cage subsidence (> 2 mm) was observed in 5% of the patients in the alendronate group and 29% in the control group, and while no vertebral fractures were observed in the alendronate group, 24% of patients in the control group presented subsequent fractures.⁸⁰

Therefore, according to the authors of this study as well as a recent expert editorial, a protocol of alendronate initiated immediately after surgery and maintained for 3 months postoperatively seems to provide significant benefits for patients with osteoporosis undergoing spinal fusion.^{80,81} Similarly, in those patients already under use of such drug, there is no clinical evidence supporting its discontinuation either before or after spinal fusion.

Partial Estrogen Agonists and Antagonists

Although they were primarily developed to decrease postmenopausal symptoms, estrogen agonists have been shown to significantly increase BMD and, therefore, have also found application as an adjuvant treatment in patients with severe osteoporosis and suboptimal management with first-line drugs (such as bisphosphonates). Although estrogen agonists strongly decrease the incidence of hip and spine fractures they are not routinely used as first choice for the treatment of osteoporosis, as its use in women over the age of 60 years have been demonstrated to increase the risks of venous thromboembolism, coronary artery disease, and breast cancer. These medications also do not possess a long-term durable effect in terms of bone quality (e.g. if stopped before 60 years of age, they are not able to prevent fractures later in life).²⁰⁻²²

Selective estrogen receptors modulators (SERMs) such as Raloxifene and Bazedoxifene have also been shown to decrease the risk of vertebral fractures by 30–50% in women belonging to the high-risk group according to the Fracture Assessment Risk of the WHO. Additionally, the risks of thromboembolism with these medications are lower in comparison with the standard estrogen replacement therapy.^{22,23}

Parathyroid Hormone

Parathyroid hormone (PTH) has the ability to improve bone quality by specifically targeting the bone microarchitecture.

In fact, by improving the density of the trabecular connectivity and collagen cross-link formation, therapy with PTH analogues has been shown to lead to increased bone strength and mechanical resistance.²⁴

This effect on the microarchitecture of bone does not occur with biphosphonates and, therefore, some authors believe that there may be an opportunity for combining both classes of medications. The main drug in this class is teriparatide, a recombinant human PTH. Although not routinely used in the clinical practice, the greatest benefits of PTH analogues are seen in patients with multiple risk factors for osteoporosis, such as: low body mass index, use of glucocorticoids and gastrointestinal disorders that inhibit the absorption of vitamins and electrolytes.^{22,24}

In relation to its use in spinal surgery, a recent prospective randomized trial demonstrated that daily subcutaneous injection of 20 µg of teriparatide (Forteo®), form of administered for 2 months before and 8 months after surgery, was more effective in promoting fusion than biphosphonates (bone union rate of 82% in the teriparatide group versus 68% in the bisphosphonate group) after instrumented lumbar posterolateral fusion with local bone grafting in women with post-menopausal osteoporosis.⁸²

Therefore, according to a recent systematic review, there is already evidence that recombinant PTH improves the fusion rate and fusion mass microstructure, and therefore it constitutes an interesting option for treating osteoporosis in patients requiring complex spine surgery.

■ COMPLICATIONS OF DEFORMITY SURGERY IN OSTEOPOROTIC PATIENTS

As already mentioned several studies have demonstrated that osteoporosis is an important risk factor for complication after deformity surgery.^{4,25} Although most of these complications are related to pseudarthrosis and hardware loosening, it is important to remember that other complications, such as graft subsidence, adjacent segment fracture and even infection (as the results of a recent study seems to suggest)²⁶ occur more often in complex spine surgery in osteoporotic patients.

Similarly, in the setting of adult degenerative scoliosis (the scenario in which most of the deformity surgeons will face osteoporosis), it has already been demonstrated that patients with osteoporosis present higher complications rates than those without it. Early complications include pedicle fractures and compression fractures. Late complications include pseudarthrosis with instrumentation

failure, adjacent-level disc degeneration, compression fractures, and progressive kyphosis.¹

Pseudarthrosis

Multiple studies have already demonstrated that pedicle screw fixation alone is less effective in osteoporotic bone.^{4,27-29} Previous investigations regarding the failure mechanisms after pedicle screw fixation have demonstrated that translational motion, causing a “windshield wiper” effect and leading to loosening of the screws is one of the most important causes of pseudarthrosis after spinal instrumentation in osteoporotic patients (Figs. 116.1A to E).^{30,31}

Regarding adult complex deformity surgery, it is important to remember that it has already been shown that incomplete sacropelvic fixation significantly increases the risks of pseudarthrosis and that the clinical outcomes scores are adversely affected when pseudarthrosis develop (Figs. 116.2A to E).³² Therefore, it is highly advisable that major thoracolumbar fusions for treatment of deformity in patients with osteoporosis include a strong sacropelvic fixation.

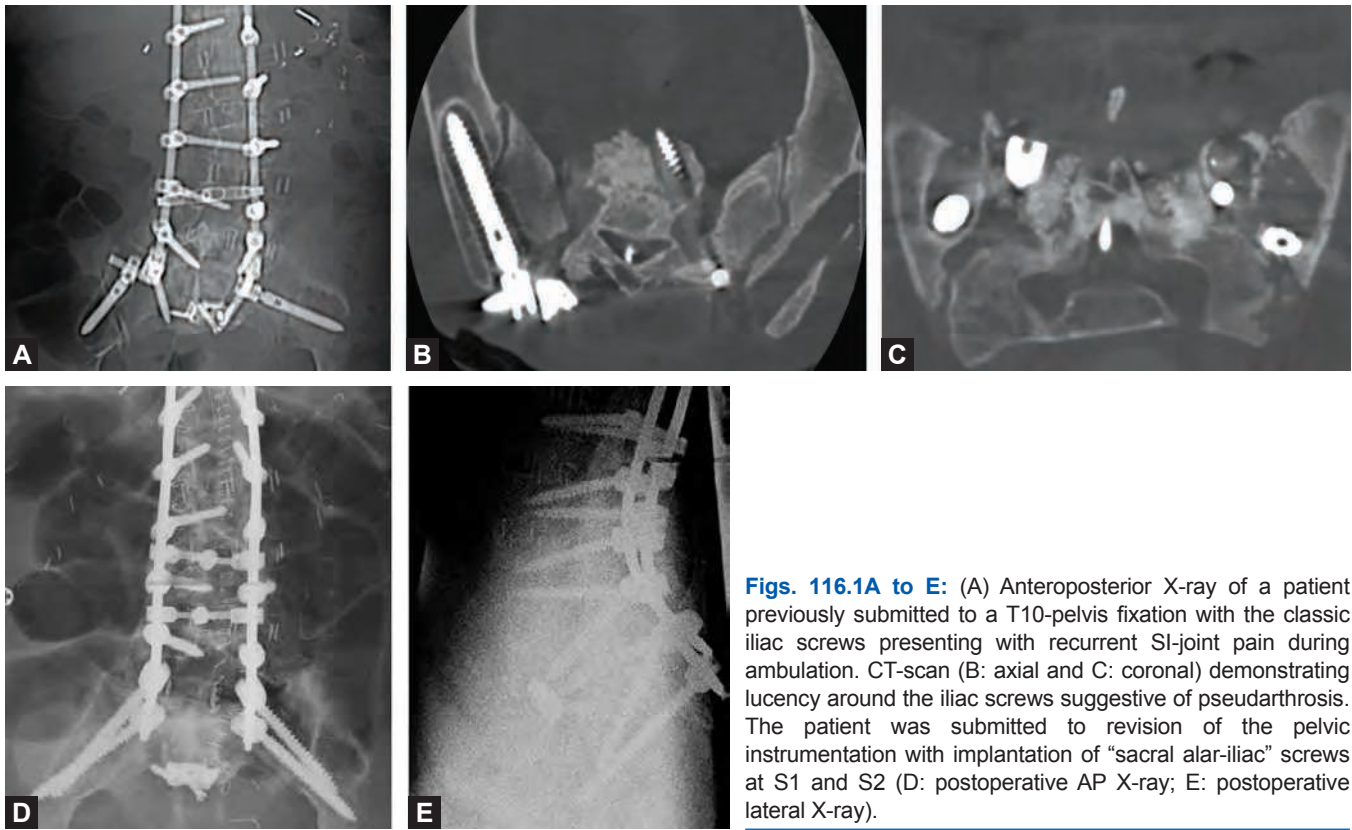
Most series dealing with complex deformity surgery in the elderly report a very high risk of overall complications at the long-term follow-up (more than 30% at 5 years).³³ Most of these complications are related to mechanical failure and pseudarthrosis, which usually require a second procedure in order to deal with broken rods, loose screws or to extend the fusion to adjacent affected levels.^{34,35}

Graft Subsidence

Implant subsidence is a frequent complication of interbody fusion in osteoporotic patients after both lumbar and cervical fusion.³⁷ As the interface between a spinal implant and vertebral body, the endplates play an important role in sharing the axial load forces between adjacent vertebral bodies. A cadaveric study demonstrated that BMD inversely correlates with the rates of lumbar endplate failure after axial load.³⁶

Adjacent Segment Fracture

In a study comparing BMD using Hounsfield units (HU), a quantitative scale for describing radiodensity, from computerized tomography scans in patients with adjacent segment fractures following spinal fusion, the authors demonstrated that HU values at the fracture level were



Figs. 116.1A to E: (A) Anteroposterior X-ray of a patient previously submitted to a T10-pelvis fixation with the classic iliac screws presenting with recurrent SI-joint pain during ambulation. CT-scan (B: axial and C: coronal) demonstrating lucency around the iliac screws suggestive of pseudarthrosis. The patient was submitted to revision of the pelvic instrumentation with implantation of "sacral alar-iliac" screws at S1 and S2 (D: postoperative AP X-ray; E: postoperative lateral X-ray).

significantly lower in the fracture group compared to controls. Similarly, the global assessment across the whole thoracic and lumbar spine using HU units demonstrated significantly lower values in the fracture group, suggesting that osteoporosis may be an important risk factor for adjacent-segment fracture following a spinal fusion.³⁸

Infection

In addition to commonly known risk factors for surgical site infections such as age, obesity, diabetes, tobacco use, and estimated blood loss, a recent study demonstrated that osteoporosis may also be an independent risk factor for postoperative infection after spine surgery.²⁶

SALVAGE TECHNIQUES FOR DEFORMITY SURGERY IN OSTEOPOROTIC PATIENTS

Cement Augmentation

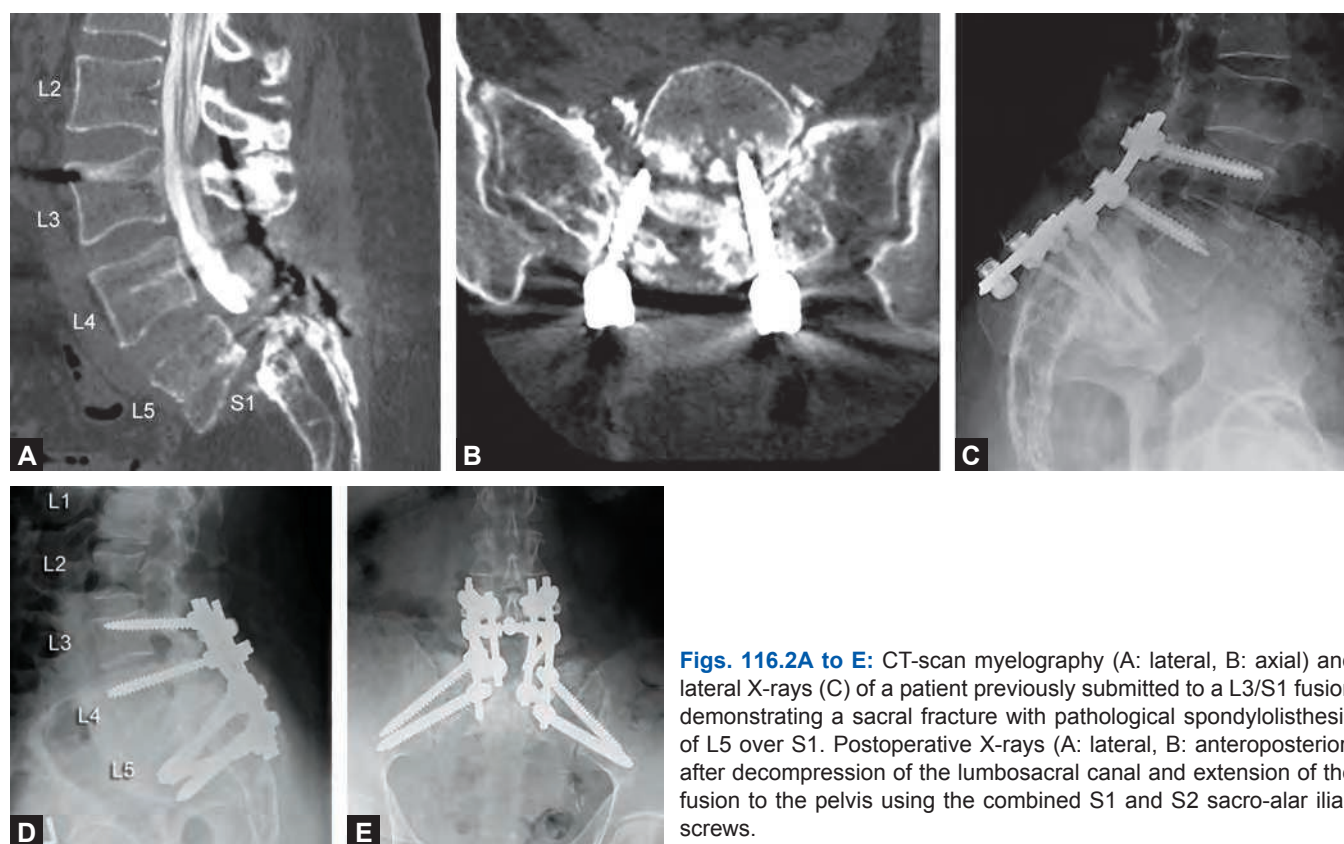
A recent cadaveric study has demonstrated that cement (polymethyl methacrylate [PMMA]) augmentation of pedicle

screws instrumentation in osteoporotic vertebrae using the conventional kyphoplasty technique significantly increased the pullout strength of screws in comparison to a control vertebrae with no cement augmentation.³⁹

A recent survey among Germans spine surgeons (composed of both orthopedic and neurosurgeons) demonstrated that nearly 80% of the participants routinely use cement-augmented pedicle screws in their daily practice. Moreover almost 2/3 of the specialists affirmed that they also use cannulated screws or other specially designed screws in the setting of osteoporosis.⁴⁰

Another study which investigated the relationship of polymethyl methacrylate augmentation and the incidence of postoperative pseudarthrosis after instrumentation of osteoporotic vertebral fractures found that the incidence of clear zones around the pedicle screws were significantly lower in the cement-augmented group in comparison with the control group (29.4% vs 71.4%). Moreover long-term loss of intraoperative curve correction was significantly lower (3 degrees vs 7.2 degrees) and the fusion rates were significantly higher in cement-augmented group (94.1% vs 76.1%).⁴¹

A study which compared the pullout strength of fenestrated titanium screws specifically designed for cement



Figs. 116.2A to E: CT-scan myelography (A: lateral, B: axial) and lateral X-rays (C) of a patient previously submitted to a L3/S1 fusion demonstrating a sacral fracture with pathological spondylolisthesis of L5 over S1. Postoperative X-rays (A: lateral, B: anteroposterior) after decompression of the lumbosacral canal and extension of the fusion to the pelvis using the combined S1 and S2 sacro-alar iliac screws.

augmentation with standard titanium screws demonstrated that the fenestrated screws demonstrated significantly greater insertion torques, leading to more effective and lasting purchase in patients with poor bone quality.⁴²

Bone Morphogenetic Protein

The use of bone morphogenetic protein (rhBMP-2) has been evaluated as an adjunct for fusion in the elderly.⁴³ A prospective randomized controlled trial comparing bone grafting with rhBMP-2 versus iliac crest bone graft for lumbar spine fusion in patients over 60 years of age demonstrated greater improvement in Oswestry Disability Index (ODI) and Short Form-36 physical component score (SF-36) in the rhBMP-2-infused graft group in comparison with the iliac crest bone graft group. The study also demonstrated lower rates of complications and revision procedures in the rhBMP-2 group. Additionally the fusion rates as evaluated by CT-scan were significantly higher in the rhBMP-2-infused graft group in comparison with the iliac crest bone graft group.⁴³ In a follow-up cost-analysis, although the mean cost of the initial admission

was slightly higher (\$36,530) in the rhBMP-2 group than in the iliac crest bone graft group (\$34,235), the total cost of care over 2 years was higher in the iliac crest bone graft group (\$42,574) in comparison with the rhBMP-2 group (\$40,131).

Special Pedicle Screws

Although still not widely available in the clinical practice, a newly designed “expandable” pedicle screw has been demonstrated to be able to support an axial load 25% greater than the maximum load supported by standard pedicle screws. Additionally, the energy required to cause bone-implant failure was also statistically greater for the expandable screw when compared with a traditional pedicle screw.⁴⁴

Intraoperative Image-guidance

Besides the advantage of improving the rates of successful pedicle screw placement in situations of distorted anatomical landmarks, intraoperative navigation enables placement of longer screws with bi-cortical purchase

(both in anterior and posterior approaches), as well as the option of different trajectories of screw placement. A more lateral pedicle screw trajectory which engages the lateral cortex of the vertebral body has been shown to increase the axial pullout strength by approximately 30%, therefore significantly minimizing pedicle screw loosening in patients with poor trabecular bone.⁴⁵

Extension to the Pelvis

The ideal technique for spinal instrumentation in a patient with poor bone quality involves the use of multiple points of fixation above and below the apex of the deformity.¹ The use of pelvic fixation is an important tool in deformity surgery (especially in osteoporotic patient), as it provides a strong anchor for long thoracolumbar constructs.²

Pelvic fixation is routinely used in spinal deformity surgery for two main purposes: to enable better correction of the deformity (especially if the apex or the curve is in the lumbar spine) and to increase the stability of fixation at the lumbosacral junction in order to avoid a pseudarthrosis. Pelvic fixation also enables correction of the pelvic obliquity in the context of long thoracolumbar constructs.

The two classic procedures used for pelvic fixation are the “Galveston technique” and the “Iliac wing screw.”⁴⁶ The Galveston technique was developed by Allen and Ferguson in the early 1980s and consists of a rod inserted longitudinally between the two cortical plates of the ilium.⁴⁷ Although this technique received significant enthusiasm by the spine community at the time of its proposal, undergoing several technical modifications throughout the years,⁴⁵ it has the inherent disadvantage of requiring complex three-dimensional bending of the rods.

At the present time the most widely performed technique for pelvic fixation is the use of pelvic screws inserted into the iliac wing with an entry-point at the posterior superior iliac spine (PSIS).^{45,48,49} Biomechanical studies have demonstrated that iliac screws provide a pullout resistance at least three times greater than the standard Galveston technique.⁵⁰

Although widely used in deformity surgery, sacral fractures and tumors, iliac screws still have some important drawbacks. Due to their lateral entry-point in the ilium and their craniocaudal proximity to S1 screws it is almost impossible to bend the rod to fit into the tulip head of both screws, so that, in most cases, a side-to-side connector that crosses the paraspinal muscles is often required. Moreover, because the entry-point of the classic iliac screw at the PSIS is very superficial, some patients (especially

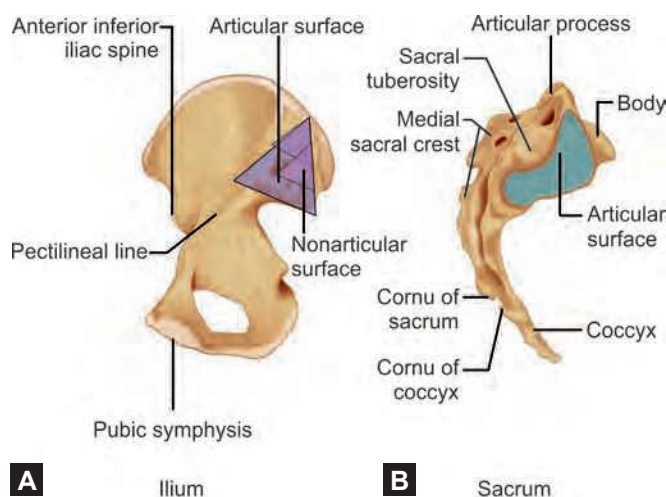
those with low BMI) may present with an unaesthetic and uncomfortable prominence of the screw head under the skin at its entry point.⁵¹ Also, because the harvesting site of the iliac crest graft (whenever used) is usually in close proximity to the entry-point of iliac screws at the PSIS, there may be the potential for significant compromise of the bony integrity of the ileum with the potential for fracture of the superior portions of the ileum.

Several studies have demonstrated that SI-joint pain may be an important cause of the so-called “failed back syndrome,” with an estimated incidence between 29% and 40% of cases in which postoperative chronic low-back pain is observed.^{32,57,58} A finite element study, for example, demonstrated that there is increased motion and stress within the SI joint in patients submitted to L4-L5, L5-S1, and L4-S1 instrumentations in comparison to non-operated patients.³² Additionally, other studies have demonstrated an increased local uptake in the SI joint on both conventional bone scintigraphy (bone-scan) and single-photon emission computed tomography (SPECT) after lumbar fusion, suggesting that biomechanical changes after lumbosacral fusion may contribute to SI joint stress, inflammation, degeneration and pain.⁵⁴ Therefore, “disrupting” and fusing the SI joint may be a method of avoiding such a painful occurrence.

The technique for placement of “sacral alar-iliac” screws was first described in 2007 in a series of 32 pediatric patients,⁵² and was later employed by clinical studies of deformity surgery in the adult population.⁵³⁻⁵⁵ This technique allows for a screw entry point between the S1 and S2 posterior foramina with the screw traversing the SI joint and then into the ileum. The advantage of this modified screw entry point allows for a low-profile screw (related to their deeper entry-point) and easier alignment with the upper pedicle screws. Due to the fact that the superior portion of the lateral sacral projection to the ilium corresponds to a nonarticular area (Figs. 116.3A and B) it has been reported that “sacral alar-iliac” fixation may not necessarily violate the true SI joint, although in according to a previous report such violation occurs in approximately 60% of the cases.⁵⁶

Surgical Anatomy of Sacral Alar-Iliac Screws

In order to properly describe the anatomical landmarks for placement of “sacral alar-iliac” screws, a basic review of the anatomy of the posterior sacral region is necessary. The human sacrum is a large triangular bone com-



Figs. 116.3A and B: (A) Medial view of the Ilium. The projection of the lateral sacral mass on the outer table of the posterior ilium has a triangular shape. The superior portion of the projection consists mainly of a nonarticular surface, while the inferior one (with an anterior upward limb) consists to an articular surface. (B) Lateral view of the sacrum. Note the similar form of the articular portion of the sacrum (called “auricular surface”—in blue) and the articular portion of the ilium.

posed by five separate vertebrae that are fused along with their intervening intervertebral discs. The dorsal surface of the sacrum is convex in shape and marked by several longitudinal crests coursing in a rostrocaudal direction (Fig. 116.5). The prominent “median sacral crest” is derived from the rudimentary spinous processes of the upper three or four sacral vertebrae that fused together. Usually it is possible to observe 3 or 4 median tubercles (the remnant of the rudimentary spinous process), with the S1 tubercle being more prominent and distinct from the rest.⁶⁴

Lateral to the “median sacral crest”, on each side, there is a depression called the “sacral groove”, which is formed by the fusion of the rudimentary sacral laminae. Lateral to sacral grooves there is a series of indistinct intermediate tubercles (representing the fused articular processes of the sacral vertebrae) which form another longitudinal crest, called the “intermediate crest”. The intermediate tubercles of the fifth sacral vertebra form the so-called “sacral cornua”, which articulates with the corresponding coccygeal cornua.

The four posterior sacral foramina are located laterally to the “intermediate sacral crest”. They are usually smaller in size and less regular in form than the anterior sacral foramina and transmit the posterior divisions of the sacral nerves.⁶⁵ The lamina of the fifth sacral vertebra (and sometimes those of the fourth) commonly fail to fuse at

the midline, giving rise to the “sacral hiatus”, a bony gap in the posterior wall of the sacral canal which can be used for anesthetic purposes, such as the “caudal epidural block.”⁶⁶

Laterally to the posterior sacral foramina there is another crest called the “lateral sacral crest”, which forms the boundary between the “body of the sacrum” and the “lateral sacral mass” (also called “pars lateralis”). The “pars lateralis” is formed by the embryological union of the transverse processes of the primitive sacral vertebrae. Because the superior parts of these lateral portions resemble wings (in Latin: *ala*) they are conventionally called “sacral alae”. The sacral alae present a large triangular surface which supports the psoas major muscle and the lumbosacral trunk.⁶⁴

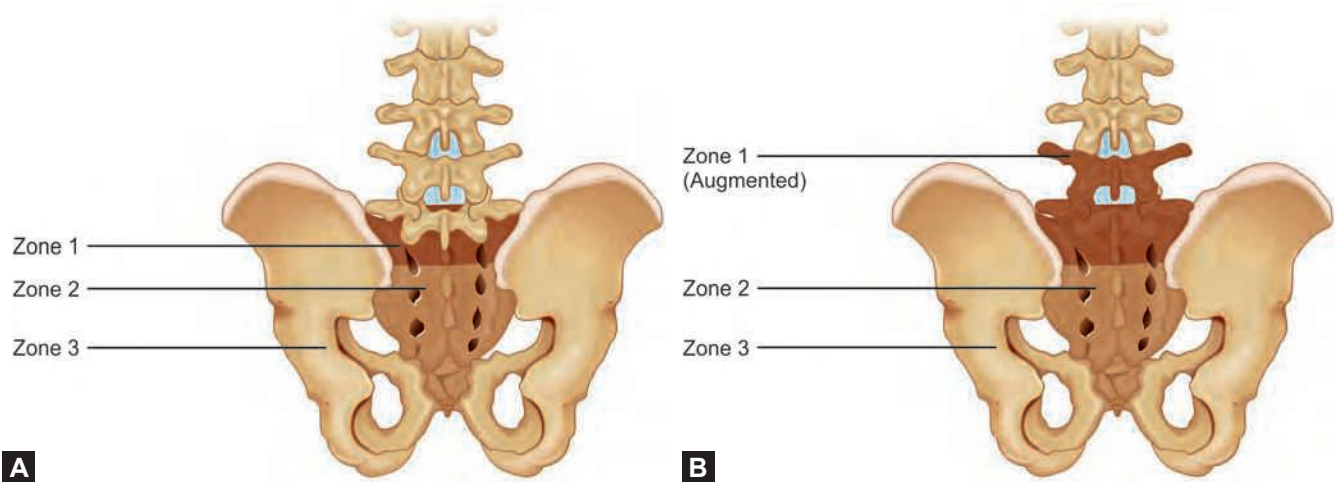
Within the posterior sacral foramina there is a fibrous membrane thought to be analogous to the *ligamentum flavum* of the mobile vertebral column.⁶⁷ A foraminal arterial branch (arising from the lateral sacral artery) is almost invariably present within the foramina. During lateral subperiosteal dissection of the posterior surface of the sacrum in order to identify the entry-point of the “sacral alar-iliac” screw, it is frequent to observe bleeding from this artery, which can be easily controlled with monopolar or bipolar coagulation.

Biomechanics of Pelvic Fixation

From the biomechanical standpoint the lumbosacral base may be divided into three different zones (Fig. 116.4A).⁵⁹

Zone 1 consists of the S1 vertebral body and the cephalad margins of the sacral *alae*. The most common techniques for fixation in zone 1 involves placement of S1 pedicle screws, with the ideal trajectory converging toward the midline, and preferentially, with bicortical purchase of the sacral promontory. Although S2 and S3 pedicle screws are feasible, they do not add much biomechanical strength to the construct due to their short length, and therefore are rarely used. As zone 1 does not provide numerous options for biomechanically-robust fixation, it can be augmented by providing structural anterior inter-body support between L5-S1 and L4-L5-S1 (Fig. 116.4B). It has already been demonstrated, for example, that adding an anterior strut at the L5-S1 or L4-L5 levels changes the instantaneous axis of rotation (IAR) cephalad and, therefore, decreases S1 screw flexion-extension moment by 33%.⁶⁰

Zone 2 includes the sacral *alae* (including the portion of S1 at this level) through the distal sacrum. Although providing some additional biomechanical strength to the construct, zone 2 fixations does not enable major distal



Figs. 116.4A and B: Biomechanical division of the lumbosacral-pelvic junction. (A) Zone 1 comprises the S1 vertebral body and the cephalad margins of the sacral alae above the S1 foramen. Zone 2 includes the rest of the sacral alae and the distal sacrum. Zone 3 consists of the ilium. (B) The biomechanical strength of zone 1 constructs can be “augmented” by adding an anterior column support to the lower lumbar levels (L5/S1 and L4/L5).

Courtesy: Reprinted with permission from Kim D, Betz R, Huhn S, Newton P (Eds). *Surgery of the Pediatric Spine*. Pg 718, 766, Thieme, New York, 2008.

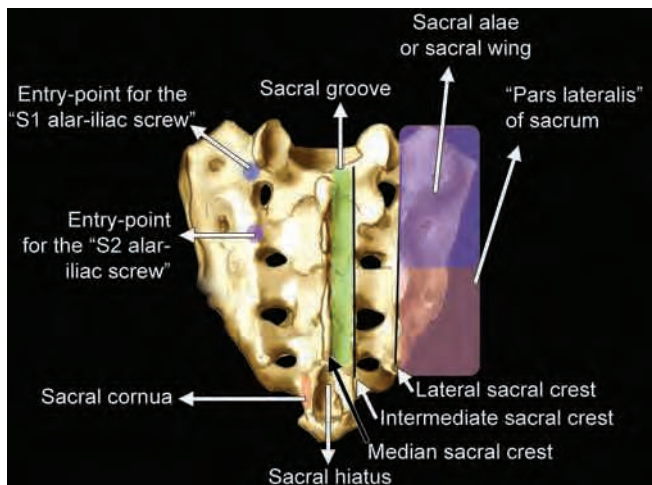


Fig. 116.5: Depiction of the posterior anatomy of the sacrum as well as important landmarks for placement of “sacral alar-iliac” screws. Two different entry-points are possible for “sacral alar-iliac” fixation. The first option is the use of an entry-point above the S1 foramen at the level of the “lateral sacral crest” (S1 sacral alar-iliac screws). The second option is using an entry-point localized between the S1 and S2 foramina, also at the level of the “lateral sacral crest” (S2 sacral alar-iliac screw). In cases in which a stronger biomechanical anchor is necessary it is possible to insert both S1 and S2 sacral alar-iliac screws.

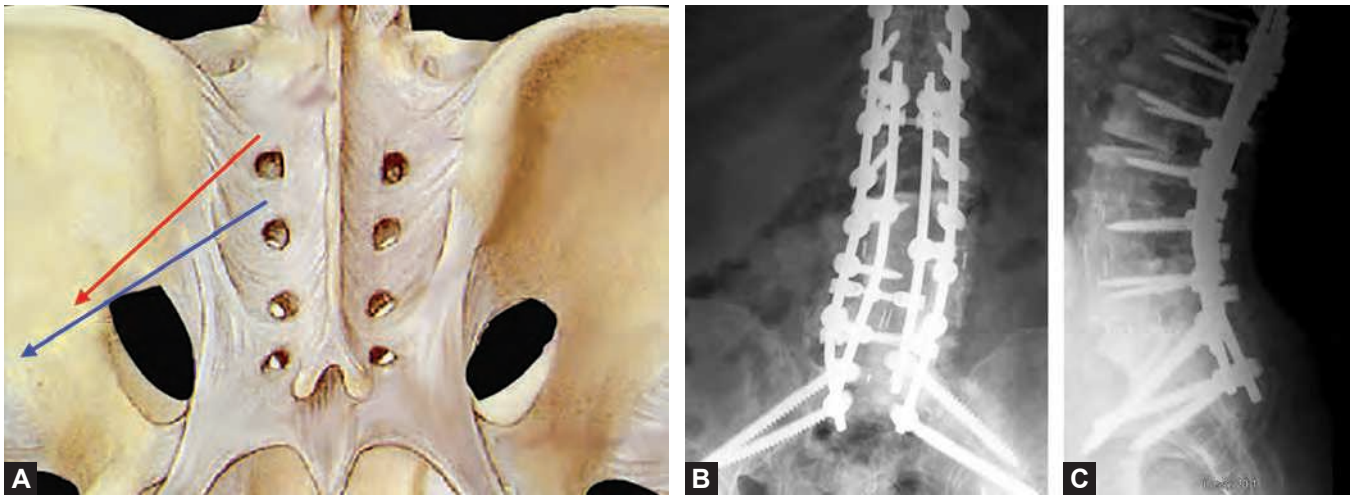
anchorage points because of the constraints of the sacral anatomy as well as the high porosity of the medullary bone of the sacrum. Previous studies have shown that

the mid-anterior cortex of the sacral *alae* is the portion of the sacrum with the higher bone density, providing the best screw purchase for zone 2 fixation.⁶¹ Fixation options for zone 2 include: alar screws, sacral hooks and, less commonly, sublaminar wires.⁶² Because of its diverging nature and its multiple fixation points anterior to the IAR, S1 alar screws provides a fixation with intermediate strength between S1 screws alone and S1 screws supplemented by iliac screws.⁵⁹

Zone 3 includes the ilium bilaterally. This region provides the strongest anchorage point for long thoracolumbar fixation constructs. As already mentioned, the Galveston technique, although providing a strong distal fixation option, is technically challenging as it requires a sharp bending of the rod so that it penetrates the ilium in an oblique fashion in the region just above the sciatic notch.⁶³ This form of fixation also provides little resistance to axial pull-out, an important disruptive force during spinal flexion. Finally, studies have demonstrated that micromotion of the SI joint may lead to erosion of the ilium by the rods with symptomatic early loosening.⁵⁹ Therefore, as already mentioned, the Galvestone fixation technique has fallen in disuse, being rarely seeing in current surgical practice.

Operative Technique of Sacral-Alar Screws

In most cases in which pelvic fixation is selected, the fusion length often spans most of the lumbar spine, often extending



Figs. 116.6A to C: (A) Graphic representation of the entry-points and ideal trajectory of the S1 and S2 sacral alar-iliac screws. (B and C) Anteroposterior and lateral (respectively) plain X-rays after a revision surgery for pseudarthrosis of a previous pelvic fixation with iliac wing screws in which a stronger distal anchorage at the pelvis was necessary. Note the placement of both S1 and S2 sacral alar-iliac screws converging toward the upper limit of the sciatic notch.

also into the thoracic spine. It is important to remember that, in order to enable proper identification of the anatomical landmarks for the insertion of “sacral alar-iliac” screws, it is necessary to extend the surgical incision caudally at least 2–4 cm in comparison to that required for placement of S1 screws. In fact, the dissection may need to be extended as distal as the third or fourth sacral segment. In selected cases, it has already been shown that ‘sacral alar-iliac screws’ may also be inserted through a minimally invasive technique.⁵⁴

As the sacral *alae* (or sacral wings) are very wide, there are several potential entry-points in the S1 and S2 portions of the sacral *alae*. Our preferred starting point for the “sacral alar-iliac” screw is located midway between the S1 and S2 foramen and at the level of the “lateral sacral crest” (see Fig. 116.5). Such a starting point usually lines very well with the entry point of the S1 pedicle screw and those of the lower lumbar spine so that no rod bending (or usually a very small medial bending of the rod) is necessary. Such a starting point is located about 25 mm inferior to the superior aspect of S1 and 22 mm lateral to the midline of S2 in the coronal plane.

The ideal trajectory of the “sacral alar-iliac” screw involves approximately 40° of angulation in the anterior direction and 40° of angulation in the caudal direction. Although it is useful to have such angles in mind, the final craniocaudal angle will be ultimately determined by the anteroposterior (AP) and inlet view on fluoroscopic or intraoperative navigation images.

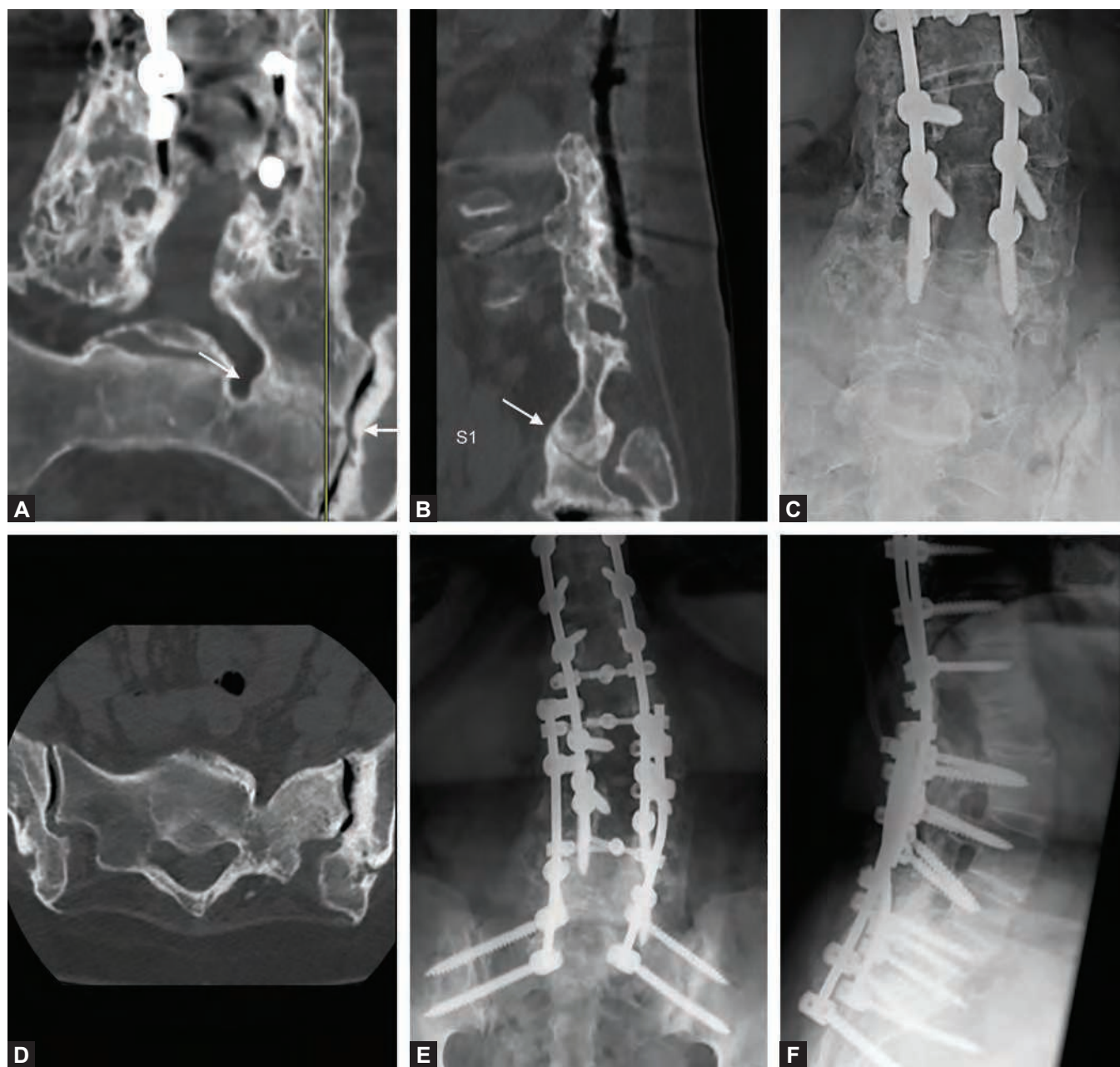
Before reaching the SI joint the “sacral alar-iliac” screw usually crosses a mean distance of 35 mm inside of the sacral bone. After crossing the SI joint, in most of the cases, it is possible to progress the screw inside the ilium additional 35 to 65 mm, so that the final length of a standard “sacral alar-iliac” screw ranges from 70 to 100 mm.

Although most previous reports have described the “sacral alar-iliac” screw as beginning at the alar portion of S2, we have been able to place both a S2-iliac and S1-iliac screw (Figs. 116.6A to C).

Although the classic technique for placement of iliac screws often involves the use of lateral fluoroscopic guidance,⁴⁸ in our experience, the AP and inlet views allow optimum visualization for safe placement of ‘sacral alar-iliac’ screws, as it enables both visualization of the screws crossing the SI joint as well as avoidance of inferior violation toward the sciatic notch.

After defining the initial entry-point according to the aforementioned landmarks, a small initial hole is made with a burr in order to accommodate a power-drill or hand-held probe. At this point, AP-fluoroscopic guidance is used to determine the exact craniocaudal angle of the “sacral alar-iliac” screw. The ideal trajectory is immediately above the notch so that the screw threads are in contact with the cortical bone forming the upper limit of the notch, providing optimal pullout-out strength (Figs. 116.7A to F).

Due to the specific trajectory of the “sacral alar-iliac” screw, anterior violations toward the pelvis are much more



Figs. 116.7A to F: CT-scan (A: coronal, B: sagittal, D: axial) and plain X-rays (C: anteroposterior) of a patient previously submitted to T4/L4 fusion for adult degenerative scoliosis demonstrating fracture of the left sacral alae (left white arrow in A and B) despite the good fusion mass observed between L3 and L5. Note also the presence of air inside the left S1 joint, a sign of advanced spondylotic changes (right arrow in A). Postoperative X-rays (E: AP, F: lateral) after extension of the fusion to the pelvis using the combined S1 and S2 sacro-alar iliac screws.

rare when compared with the classic iliac screws. The width of this screw (usually 8 to 10 mm) combined with such a long bony trajectory (usually 70 to 100 mm, including the two cortical surfaces of the SI-joint) the “sacro alar-iliac” has a very strong purchase.

Because the entry-point for the classic iliac screw at the PSIS is much more lateral in comparison to the entry-points of lumbosacral pedicle screws, it is usually very difficult to bend a rod in order to directly connect the iliac screws with the rest of the lumbosacral screws. This mismatch often

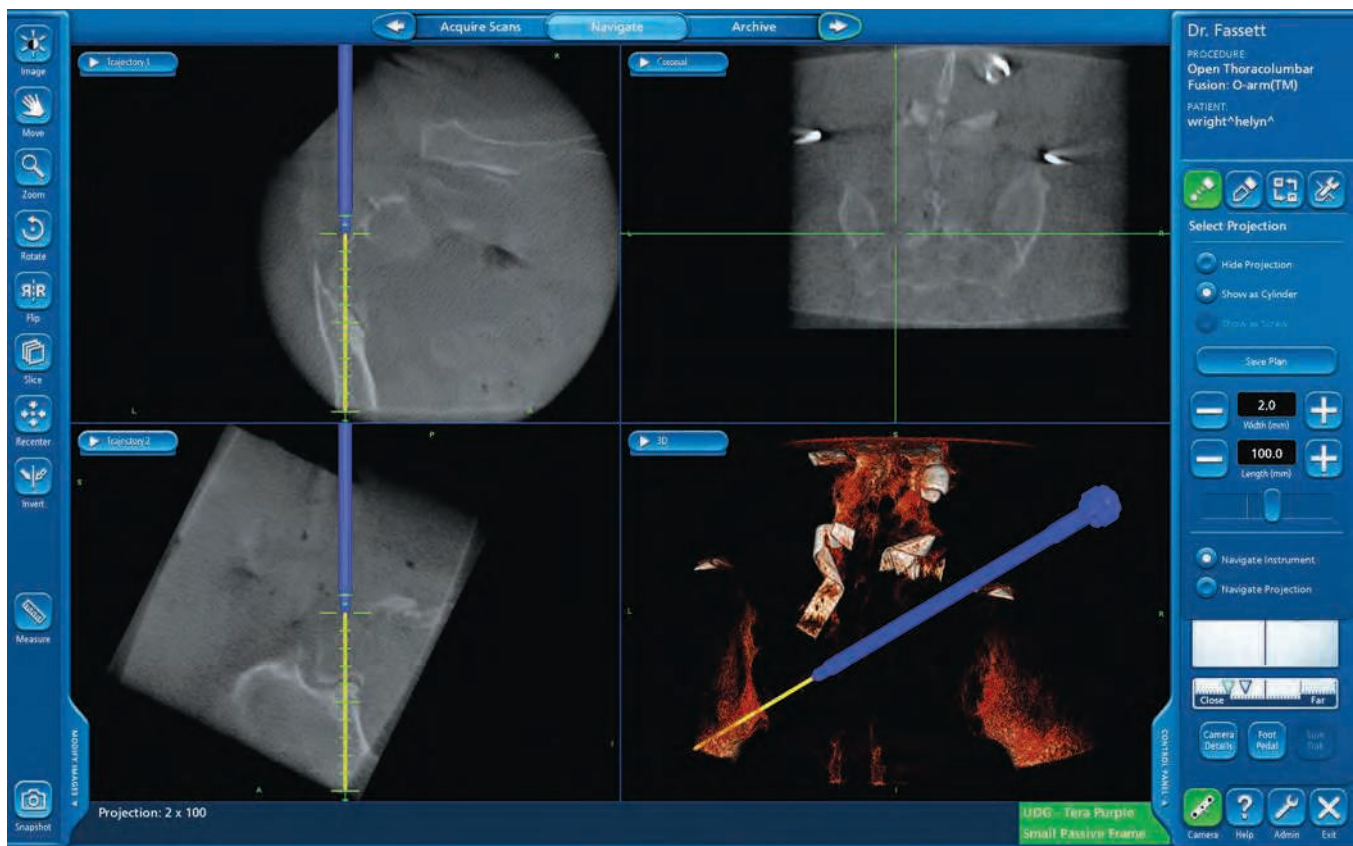


Fig. 116.8: Images of intraoperative CT (O-arm®)-based navigation for placement of sacral alar-iliac screws. Note the ideal projection of the screw crossing the SI joint right above the sciatic notch in the “in-line” trajectories (superior and inferior left) and coronal plane (superior right) as well as anteroposterior radiographic projection).

leads to the necessity of a separate incision in the lumbar fascia as well as the use of off-site connectors. Because the entry-point of the “sacral alar-iliac” screw lies more medially (at the sacral *alae* and not at the iliac bone) is it much easier to connect it with lumbosacral screws, so that usually no (or very little medial bending) of the rod is necessary. Furthermore, in comparison with classic iliac screws, the “sacral alar-iliac” screw requires much less “lordotic” bending of the caudal end of the rod.

Complications of Sacral Alar-Iliac Screws

Although the most common breach observed during placement of “sacral alar-iliac” screws is violation of the posterolateral cortex of the ilium (which usually does not result in any major complications), anterior violations may have several deleterious consequences due to the potential injury to several important vascular, neurologic and visceral structures located inside the pelvis.⁶⁸ Previous

anatomical studies examining the accuracy of “sacral alar-iliac” screws placement have shown that while the rates of posterolateral violations may reach up to 15%, anterior violations are much more rare.⁶⁹ Another dangerous complication of “sacral alar-iliac” screw placement is inferior violation of the sciatic notch. This may lead to injury of the superior gluteal artery and nerve which passes above the piriformis muscle. Injuries to structures that pass below the piriformis, such as the sciatic nerve, pudendal nerve and internal pudendal vessels are much more rare, as they would require a gross inferior violation of the sciatic due an extremely low screw trajectory. Such complications can be easily avoided with the use of plain intraoperative fluoroscopy. In our experience, intraoperative navigation guidance may even obviate the need for intraoperative real time fluoroscopy (Fig. 116.8).

Other possible complications of “sacral alar-iliac” screws are those common to other techniques of pelvic fixation, such as infection (3.7%)⁵⁴ and pseudarthrosis with

screw loosening and chronic SI joint pain. It is important to highlight that radiological studies have reported rates of radiological lucency around “sacral alar-iliac” screws of approximately 4% at a 2-year follow-up,⁵¹ however with uncertain clinical significance.⁵³

CONCLUSION

Patients with complex deformity and osteoporosis constitute a very challenging subgroup of patients in which the rates of complications (such as pseudarthrosis, graft subsidence, adjacent segment fracture and even infection) are significantly higher.^{33,34,70,25,26,72}

Nevertheless, as already previously discussed, the fact that such subgroup of patients present a higher risk of surgical complications after complex spinal procedures does not necessarily mean that the natural history of the conservative treatment provides better long-term results than surgery, nor that older patients should be denied the possible benefits of surgical intervention.⁷¹

In fact, in patients with adult degenerative scoliosis presenting with refractory pain after failed medical treatment and injections, several studies have demonstrated that a major surgical intervention (addressing not only the levels in which there is compression of the spinal canal or nerve roots but also the global spinal deformity) provides a safe “last resort” therapeutic alternative with acceptable morbidity and complication rates and sustained long-term clinical outcomes.^{33,34,70}

KEY POINTS

- Osteoporosis is defined as a BMD of 2.5 or more standard deviations below the peak bone mass for young adults (T-score \leq 2.5) on a DEXA scan.
- Patients with osteoporosis present higher risks for complications after deformity surgery. Bone quality of the spine should play an important role in the planning of surgical intervention for spinal deformities.
- Early complications of spinal instrumentation in osteoporotic patients include pedicle fractures and compression fractures. Late complications include pseudarthrosis with instrumentation failure, adjacent level disc degeneration, compression fractures, and progressive kyphosis.
- The role of osteoporosis in the etiology of adult degenerative deformity and adolescent idiopathic scoliosis is controversial.
- Biposphonates are the mainstay of treatment for osteoporosis. Vitamin D and calcium supplementa-

tion offer limited benefit but are largely used as they are cheap and relatively harmless. Parathyroid hormone has been shown to improve bone quality and could be considered preoperatively and postoperatively.

- Several adjuvant techniques, which have been shown to significantly increase the rates of obtaining a successful fusion, have been employed in deformity surgery in patients with osteoporosis, such as cement augmentation, special screws designed to osteoporotic bones, bone morphogenetic protein and extension of the fusion to the pelvis. Intraoperative navigation can assist in the placement of spinal instrumentation to insure that pelvic screws are placed in an optimal position, ultimately reducing the risks of hardware failure.
- In patients with complex deformity and significant impairment of their quality of life, several studies have demonstrated that a major surgical intervention provides a safe “last resort” therapeutic alternative. In the setting of osteoporosis, due to the higher risks of complications, objective informations regarding the risk/benefit ratio of a major surgical procedure in relation to the natural history of the disease should be clearly provided to the patient and his/her family, so that they may perform a conscious and responsible decision.

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SECTION

13

Tumor, Vascular Malformations, and Infection

Marcel F Dvorak



Primary Bony Spinal Lesions

Thomas R Hickernell, Chandhanarat Chandhanayingyong, Francis Y Lee

Snapshot

- » Patient Presentation
- » Diagnosis
- » Staging/Treatment Planning
- » Treatment Options
- » Benign Tumors
- » Malignant Tumors

INTRODUCTION

Primary spinal tumors are rare, with an estimated incidence of roughly 2.5–8.5 per 100,000 people per year.¹ They are generally more common in men, with some tumor types displaying a 2:1 incidence in men compared with women. Secondary, or metastatic, spinal tumors encompass >95% of all spinal tumors.² A majority of primary bony spinal tumors are benign, but a small percentage are malignant. The most common benign primary bony spinal tumors are giant cell tumors (GCTs), aneurismal bone cysts (ABCs), osteoid osteoma, osteblastoma, hemangioma, osteochondroma, and eosinophilic granuloma (otherwise known as Langerhans cell histiocytosis). The most common malignant primary bony spinal tumors are plasmacytoma (often a singular precursor to multiple myeloma), chondrosarcoma, osteosarcoma, chordoma, and Ewing tumors.³

The excision of bony spinal tumors is inherently more challenging than that of musculoskeletal tumors of the appendicular skeleton due to the anatomy of the spine and the need to preserve the spinal cord, its blood supply, nerve roots, and in the cervical spine—the vertebral arteries. As such, tumors of the spine are relatively unique in that their treatment falls into an area of medicine in which many different fields of practice overlap, including orthopedic surgery, radiology, neurosurgery, oncology, pathology, interventional radiology, and radiation oncology.

Whenever possible, treatment plans should be planned and carried out by coordinated, multidisciplinary teams to minimize the potential for complications, such as delayed or misdiagnosis, as well as incomplete or oncologically inappropriate resection that may lead to local or metastatic recurrence.

PATIENT PRESENTATION

The most common complaints of patients with spinal neoplasms, whether benign or malignant, are axial back pain or less commonly radicular pain, particularly at night or at rest, and progressive neurologic deficit. Suspicion for spinal tumors should be heightened when the patient has also suffered from unexplained weight loss and fevers. Rapid onset and progression of neurologic deficits are more typical of pathologic fractures or fast-growing malignant tumors, but even benign tumors can be locally aggressive and may cause rapid neurologic deterioration. Particularly when neurologic deficits progress slowly, there is often a prolonged delay between the onset and diagnosis of spinal tumors. This is compounded by the fact that there is often a delay between the onset of symptoms and the appearance of radiographic signs of disease, which may prevent a patient's case from being referred from the primary care level to that of a specialist that is more thoroughly equipped to effectively diagnose and treat the disease.

DIAGNOSIS

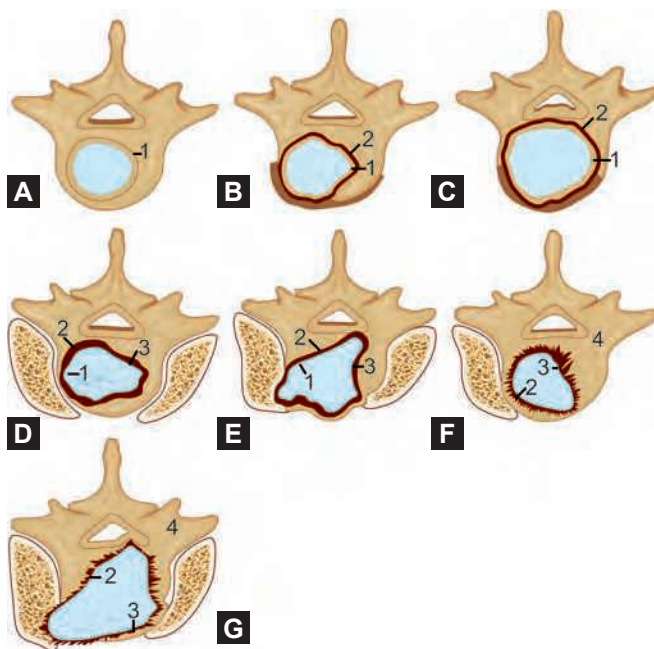
When a spinal neoplastic lesion is suspected, it must be fully imaged with X-rays, computed tomography (CT), and magnetic resonance imaging (MRI) in order to narrow the differential diagnosis. Plain radiographs are often demonstrative of primary bony spinal lesions, and occasionally diagnostic in and of themselves. Certain primary bony spinal tumors, such as osteoid osteoma or aneurysmal bone cysts, have characteristic findings on X-rays and high-quality CT scan that may not be evident if the clinician relies simply on an MRI. The diagnostic criteria of an osteoid osteoma will be discussed later in this chapter. Clinicians should be familiar with them in order to avoid excessive, unnecessary testing, and delays in diagnosis. A tissue biopsy (fine needle aspiration, core biopsy, incisional or excisional biopsy), however, is nearly always needed to make a definitive diagnosis. To identify any possible distant pathology, a full systemic workup, including CT scan of the chest, abdomen, and pelvis; nuclear medicine bone scan; and a positron emission tomography scan when available should be performed once a primary bony spinal tumor is diagnosed or highly suspected. Whenever possible, the clinician or clinical team who will be handling a patient's definitive treatment should be the ones to perform any diagnostic biopsy, in an attempt to reduce metastatic or recurrent disease as a result of inadvertent, untreated seeding of the biopsy track, or unnecessary violation of multiple fascial planes. In one study of patients who underwent en bloc tumor excision at a second institution after a failed primary attempt elsewhere, 72% suffered major complications compared to only 20% of patients whose investigation and primary surgical treatment were coordinated in a single institution. Furthermore, at an average follow-up of 37 months, 40% of the patients who required a repeat attempt at wide resection had local recurrence of their tumors, compared to only 16% of the new presentation group.⁴

STAGING/TREATMENT PLANNING

Once a definitive diagnosis has been established, oncologic and surgical staging of the tumor is necessary for the planning of treatment. The Enneking staging system,⁵ originally developed in the 1980s for the staging of appendicular musculoskeletal tumors, stages tumors from an oncologic perspective. Benign tumors are divided into S1 (latent, inactive), S2 (active), and S3 (aggressive)

(Figs. 117.1A to C), while localized malignant tumors are divided into stages 1 and 2 for low or high grade, respectively, in addition to A or B for intra- or extra-compartmental extension (Figs. 117.1D to G). Stage 3 is reserved for metastatic lesions. This system helps elucidate whether surgery may be inappropriate, curative, or just palliative, and what surgical margin may be necessary: intralesional, marginal, or wide.

Weinstein, Boriani, and Biagini later developed the WBB⁶ system (Figs. 117.1A to G) specifically for primary bony spinal tumors to aid surgical planning. In this schema, the vertebra is divided into 12 numerical zones radiating in a clockwise fashion starting from the spinous process, as well as 5 progressively deeper layers, labeled A–E, from paravertebral to dural involvement. A tumor may also be labeled “F” if it involves the spinal foramina. Longitudinal



Figs. 117.1A to G: Enneking staging for spinal tumor. (A) Inactive benign, encapsulated tumor (Stage I benign tumor), (B) active benign, encapsulated tumor (Stage II benign tumor), (C) aggressive benign tumor with expansion of the capsule (Stage III benign tumor), (D) encapsulated malignant tumor within the vertebra (Stage IA), (E) malignant tumor with extraskelatal expansion (Stage IB), (F) encapsulated malignant tumor within the vertebra with multiple infiltrative lesions in the pseudocapsule (Stage IIA), and (G) the pseudocapsule is infiltrated by aggressive tumor, which is growing outside the vertebra (Stage IIB). An island of tumor can be found far from the main tumoral mass.

Source: With permission from Boriani S, Weinstein JN, Biagini R. Primary bone tumor of the spine. Terminology and surgical staging. Spine. 1997;22:1036-44.

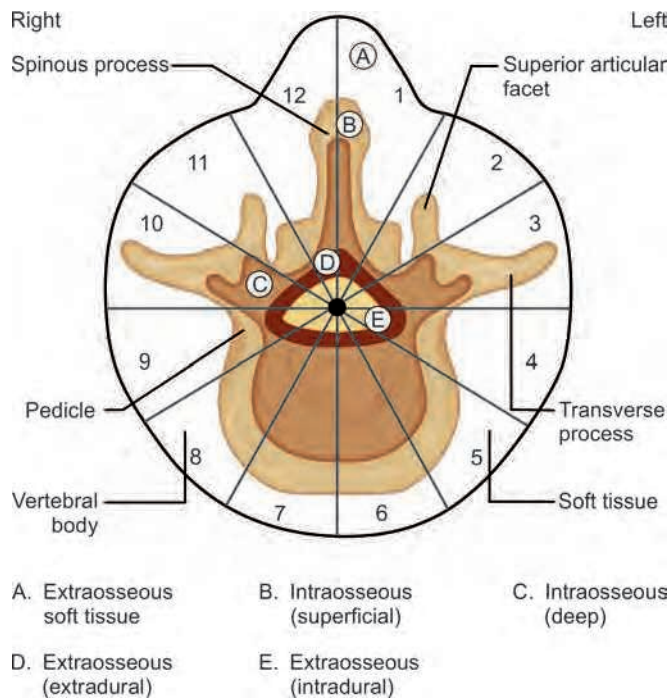


Fig. 117.2: Weinstein-Boriani-Biagini surgical staging system of spine tumors. In the transverse plane, the vertebra is divided into 12 radiating zones (numbered 1–12 in a clockwise order starting from left side of the spinous process). There are five layers from the paravertebral area to the intradural space. The tumor is identified by the numbers of the zones and the letters of the layers involved, and the vertebrae of involvement.

Source: With permission from Boriani S, Weinstein JN, Biagini R. Primary bone tumor of the spine. Terminology and surgical staging. *Spine*. 1997;22:1036–44.

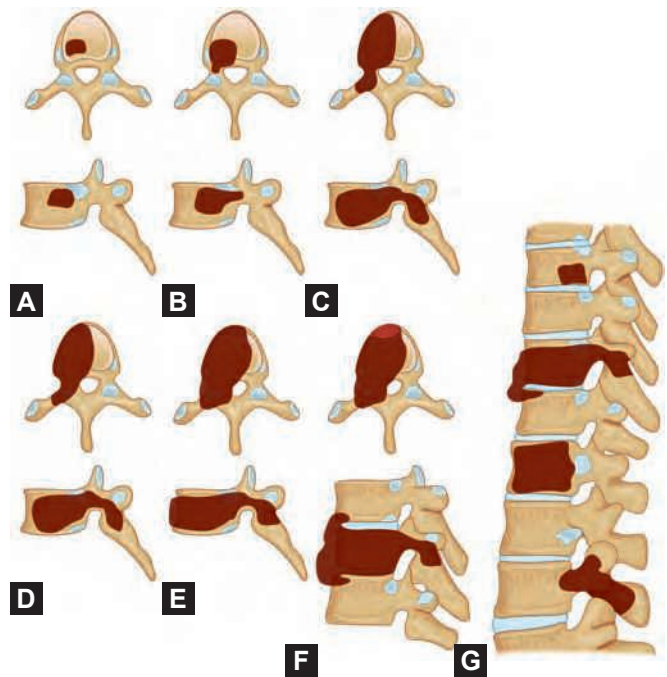
extent is denoted by indicating which specific vertebrae are involved (Fig. 117.2).

The WBB system takes into account the unique anatomy of the spinal column and the need to preserve the spinal cord while also helping to dictate surgical approach. Tomita et al. studied numerous major and minor prognostic factors for spinal tumors to describe a system consists of seven types (Figs. 117.3A to G), which is based on the most common patterns of longitudinal and horizontal spread of the tumor.

TREATMENT OPTIONS

Surgery

Benign primary spinal tumors, such as hemangiomas, are on occasion incidental findings and do not require treatment so long as they remain asymptomatic. However, when primary bony spinal tumors are the cause of significant

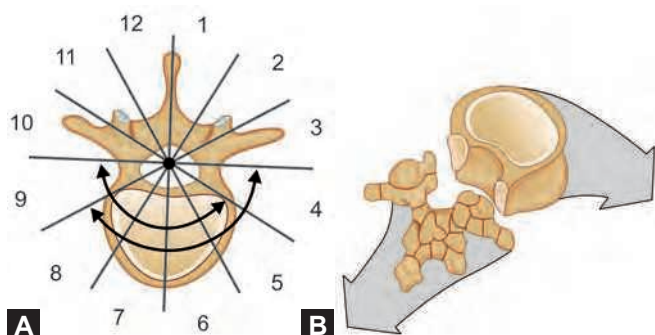


Figs. 117.3A to G: Tomita primary surgical classification of vertebral tumors classification based on the most common patterns of longitudinal and horizontal spread of the tumor. (A) type 1—localized inside the body or lamina, (B) type 2—lesion extends into the pedicle, (C) type 3—lesion extends throughout the vertebra, (D) type 4—there is epidural extension, (E) type 5—paraspinal area is affected, (F) type 6 and (G) type 7—lesions show multilevel involvement.

Source: With permission from Tomita K, Kawahara N, Baba H, et al. Total en bloc spondylectomy for solitary spinal metastases. *Int Orthop*. 1994;18:291–8.

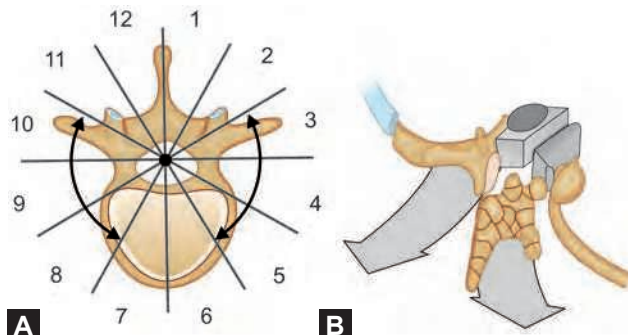
pain, progressive neurologic deficit, or threaten spinal stability, treatment is warranted. The goals of treatment are alleviation of pain, decompression of neural elements, and restoration or maintenance of spinal stability, as well as cure or palliation when cure is not deemed feasible.⁶

Tumors may be surgically excised piecemeal via curettage, otherwise known as an intralesional excision, or “en bloc,” meaning in one intact piece. En bloc excisions are generally performed via vertebrectomy (otherwise known as spondylectomy), sagittal resection, or resection of the posterior arch, depending on the oncologic and surgical staging of the tumor. Vertebrectomy (Figs. 117.4A and B) refers to the removal of the entire vertebral body, often with portions of the posterior elements. Vertebrectomy allows for appropriate oncologic margins when the tumor originates in the center of vertebral body and involves more than one pedicle (WBB zone 4–8 or 5–9 or Tomita types 1–6). Sagittal resection (Figs. 117.5A and B) is suitable for tumor in an



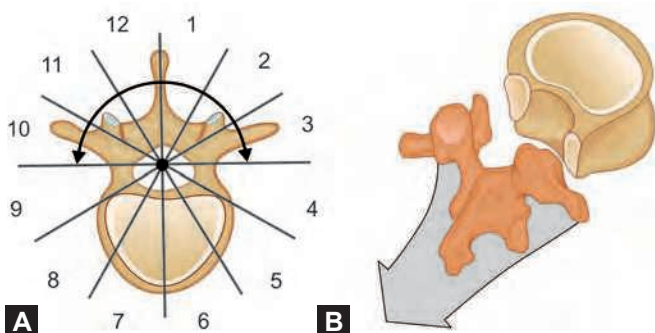
Figs. 117.4A and B: Vertebrectomy. (A) En bloc excision of a tumor occurring at the vertebral body can be performed if at least one pedicle is free from tumor. (B) A posterior stage is performed to remove the posterior elements, cut the longitudinal ligament, and separate the anterior surface of the dura from the posterior wall then the anterior approach is mandatory.

Source: With permission from Boriani S, Weinstein JN, Biagini R. Primary bone tumor of the spine. Terminology and surgical staging. Spine. 1997;22:1036-44.



Figs. 117.5A and B: Sagittal resection. (A) Tumor arising eccentrically in the body, the pedicle, or the transverse process occupies the zones 2-5 (or 8-11). (B) A posterior stage is needed to remove the posterior healthy elements. A combined posterior and anterior approach is required to safely perform the en bloc excision.

Source: With permission from Boriani S, Weinstein JN, Biagini R. Primary bone tumor of the spine. Terminology and surgical staging. Spine. 1997;22:1036-44.



Figs. 117.6A and B: Resection of the posterior arch. (A) The en bloc excision of a tumor arising in the arch is performed when the tumor occupies the zones 10-3. The pedicles must be free from tumor to obtain an oncologically appropriate specimen. (B) This procedure is performed by posterior approach.

Source: With permission from Boriani S, Weinstein JN, Biagini R. Primary bone tumor of the spine. Terminology and surgical staging. Spine. 1997;22:1036-44.

eccentric portion (WBB zones 3-5 or 8-10 or Tomita type 1, anatomic site 1 that is eccentrically located). An en bloc excision of the posterior arch (Figs. 117.6A and B) is performed when a tumor involves the posterior arch and does not involve the pedicle (WBB zones 10-3 or Tomita type 1, anatomic site 3). Instrumentation is often needed to prevent progressive deformity.

En bloc excisions may be marginal, with excision along the tumor's border or pseudocapsule, or wide, wherein the tumor is removed with at least 2 mm of healthy surrounding

tissue. The term "radical" excision should be avoided when discussing spinal tumors, as a radical vertebrectomy would technically necessitate the sectioning of the spinal cord above and below the level of excision, which in practical terms is rarely, if ever, possible.⁷ If a biopsy is performed before definitive surgical treatment, an effort should be made to clearly mark the soft tissue along the biopsy track so that it may be excised during surgery to prevent seeding of the track with tumor cells and later recurrence. While en bloc excisions with wide margins have lower rates of tumor recurrence, they are typically long operations requiring high operator skill and are associated with significant morbidity and mortality.

Following intralesional excision, adjunctive sclerosing agents, such as liquid nitrogen or alcohol, are at certain times utilized in an attempt to eradicate remaining marginal tumor cells and decrease local recurrence rates. Bone grafting or bone cement may be used to fill voids left by tumor excision or by destructive, lytic lesions in order to reduce pain, and improve vertebral stability. However, if autologous bone grafting is to be performed, it is best to access the harvest site via a separate operative setup and incision to reduce the likelihood of iatrogenically spreading the tumor.

Lytic tumors may lead to vertebral collapse and spinal instability and create postexcisional gaps following intralesional and especially en bloc excisions. As such, a combination of bone grafting and spinal instrumentation is often necessary to maintain or restore spinal instability.

Percutaneous Therapy

Some primary bony spinal tumors may be effectively treated or even cured percutaneously, such as osteoid osteomas via laser photocoagulation or radiofrequency ablation (RFA) or aneurysmal bone cysts via percutaneous intral- esional injection of a sclerosing agent such as alcohol.⁸ Percutaneous arterial embolization has been effectively used to limit the extent of intraoperative bleeding during the excision of highly vascularized tumors, and may even be curative for aneurysmal bone cysts. Percutaneous vertebroplasty or kyphoplasty, in which cement is percutaneously injected into the vertebra, can be a useful palliative procedure for patients who have painful and/or destabilizing lytic lesions that are unamenable to surgery.

Radiation Therapy

Radiation therapy is an effective tool in the treatment of fast-growing tumors, as it essentially works by damaging DNA, which prevents cell replication and causes cell death. In general, the more benign primary spinal tumors such as osteoid osteoma, osteoblastoma, and osteochondroma have poor response rates to radiation therapy. Furthermore, some benign primary tumors such as GCTs and chondroblastomas are known to rarely undergo transformation into malignant sarcomas following radiation therapy. Regardless, adjuvant, or postoperative, radiation is sometimes used following the excision of benign tumors in an attempt to kill any remaining tumor cells in the marginal tissues. Radiation therapy is an integral component in the treatment of many malignant primary spinal tumors. It is often used as a neoadjuvant (or preoperative) treatment, particularly in cases of osteosarcoma or Ewing's tumor, as this can decrease tumor bulk and facilitate surgical excision. Despite high rates of radiation resistance seen in chordoma and chondrosarcoma, adjuvant radiotherapy is routinely administered to surgical margins following the excision of malignant primary tumors.

Studies have shown that effective local control can be achieved following surgical excision of sarcomas in the extremities with a 60 Gy dose of postoperative radiation therapy. Doses of 70 Gy are typically given when there is gross evidence of residual tumor. The difficulty of administering radiation therapy in the spine, however, is that the spinal cord can typically tolerate no more than a cumulative dose of 50 Gy before patients experience radiation-induced myelopathy.⁹ As such, traditional external photon beam radiation can be extremely challenging to deliver. The fields of radiation and interventional oncology have

responded by developing several advanced methods of delivering effective doses of radiation to highly specific targets, such as intraoperative radiation therapy and brachytherapy, proton beam therapy, and high-dose conformal photon therapy.

Chemotherapy

Chemotherapy is of limited benefit in most bony spinal tumors, with the exception of osteogenic sarcomas, which has been shown to respond to combinations of several conventional chemotherapeutic agents, such as cisplatin, doxorubicin, and methotrexate, and chordomas, which have recently demonstrated sensitivities to angiogenesis and tyrosine kinase inhibitors such as imatinib (Gleevec), sunitinib (Sutent), erlotinib, and gefitinib.

Prognosis

Outcomes data on primary spinal malignancies are limited because of the rarity of the tumors and the studies available are mostly small case series of various types of tumor. However, the National Cancer Institute's SEER (Surveillance Epidemiology and End Results)³ registry helps to identify patients with primary spinal malignancies. Data from this registry have concluded that distant metastasis is a poor prognostic factor and is associated with a three- to fourfold decrease survival rate in patients with osteosarcoma, Ewing sarcoma (EWS), chondrosarcoma, and chordoma. Other independent factors that decreased survival time in osteosarcoma, chondrosarcoma, and chordoma are advanced age and increased extent of tumor invasion, including distal site metastasis.¹⁰

BENIGN TUMORS

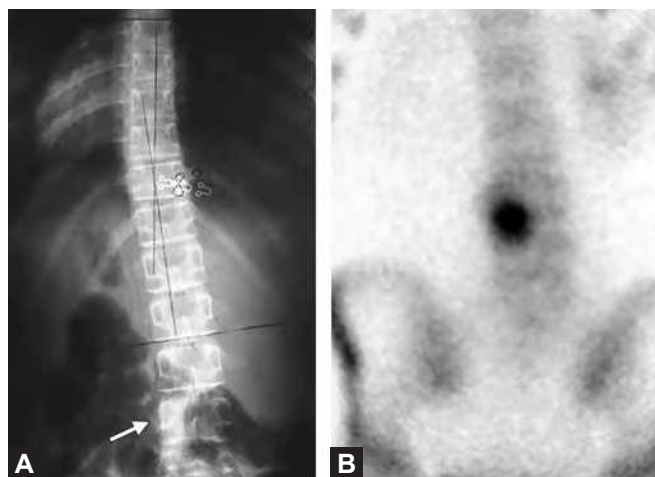
Bone Island (Enostosis)

An enostosis or bone island represents a focus of mature compact (cortical) bone within the cancellous bone (spongiosa). Bone islands are probably congenital or developmental in origin and reflect hamartomatous lesions or a failure of resorption during endochondral ossification. Bone islands are typically asymptomatic and found incidentally. Although enostoses most commonly occur in the pelvis, femur or other long bones, they can occasionally be found in the spine. Plain radiographs show a homogeneously dense, sclerotic focus in the cancellous bone with distinctive radiating streaks, so called "thorny radiations" that blend with the trabeculae of the host bone, creating

a feathered or brush-like border. On CT scan, a bone island appears as a low-attenuation focus. On MRI, the lesion shows low signal intensity, like cortical bone. Bone scan may be used to differentiate bone islands from other aggressive tumors since they are usually a “cold” lesion. However, scintigraphically active or “hot” bone islands have been reported with histological confirmation.¹¹ Physicians should be cautioned to not rely solely on a bone scan, but rather on an individual’s clinical presentation and radiographic findings. A scintigraphically “hot” bone island demands close observation and follow-up imaging studies. Differential diagnoses include blastic lesions or tumors: osteosarcoma, metastasis from prostate cancer, ganglion cyst, or an ongoing process of fracture healing. Histopathological finding reveals normal, lamellar bone with normal architecture and no cartilage or enchondral ossification. Once the diagnosis of enostosis has been made, biopsy is typically not necessary. Lesions can be observed without treatment.

Osteoid Osteoma

An osteoid osteoma is a painful, benign lesion that typically occurs in childhood and adolescence. The average age of presentation is 19 years, with >80% of the patients presenting before the age of 30 years.¹² There is a predilection for males [male:female (M:F), 2–4:1]. It is relatively common, making up approximately 10% of all benign bone tumors.¹³ The classical presentation is a patient with nocturnal pain that wakes them from sleep and is relieved by salicylates (e.g. Aspirin). Osteoid osteoma in the spine is the classical cause of painful scoliosis, seen in 75% of patients with painful scoliosis (Figs. 117.7A and B).¹⁴ Plain radiographs reveal reactive sclerosis (Fig. 117.8A). Most osteoid osteomas occur in long bones of the extremities, but essentially any bone may be involved. Osteoid osteoma of the spine accounts for 10% of all cases, distributed approximately as follows: lumbar 59%, cervical 27%, thoracic 12%, and sacrum 2%. Osteoid osteoma can occur anywhere within the bone, including cortex, medulla or in subperiosteal bone. The nidus is usually <2 cm in diameter, and clearly seen on CT, intraoperative photograph and histology (Figs. 117.8B to D). It may present with a central mineralization. The nidus releases prostaglandins, which result in pain (via Cox-1 and Cox-2). Pathological findings are a nidus of interlacing osteoid and woven bone, seen as interconnecting trabeculae or sheets with osteoblastic rimming (Fig. 117.8E). The tissue surrounding woven bone is composed of loose fibrovascular tissue with prominent osteoclasts (Fig. 117.8F).



Figs. 117.7A and B: (A) Posteroanterior radiograph of thoracolumbar spine shows levoconvex (12.5°) lumbar scoliosis with convexity toward right side and expansile lytic lesion at the region of left L4 pedicle (arrow). (B) 99 m-TcMDP bone scan showing focally increased uptake at corresponding L4 vertebra.

The lesion is benign and the treatment has traditionally been with marginal surgical resection. Surgical resection has been difficult because of the inability to locate the nidus intraoperatively. Percutaneous RFA under CT guidance has increased in popularity of late. Vanderschueren et al. reported a 79% and 96% cure rate after the first and second RFA treatment, respectively,¹⁵ although spinal deformity persisted in three of seven patients (47%) after treatment.¹⁶ Rehnitz et al.¹⁷ reported long-term (mean 38.5 months follow-up) satisfaction regarding return to normal activity and pain relief following RFA ablation. With three-dimensional CT preoperative planning and thermal protection techniques, RFA is considered safe and has a low rate of complications. Rarely reported RFA cannula breaks can lead to a short hospital stay.¹⁸ Video-assisted thoracoscopic surgery (VATS) guided by navigation system (VATS-NAV) has recently been performed in spinal osteoid osteoma to facilitate precise complete excision through a minimal approach and yield tissue pathology that RFA could not provide.¹⁹

En bloc excision has a role in patients with a fixed spinal deformity, with neurological compression, or who have failed RFA or have a tumor in a dangerous zone for RFA. Excision is a curative treatment and brings immediate relief after the operation. Spinal instrumentation and arthrodesis are recommended for cases in which resection may lead to spinal instability.

There is growing evidence that osteoid osteoma may fully resolve spontaneously over time. Selected patients

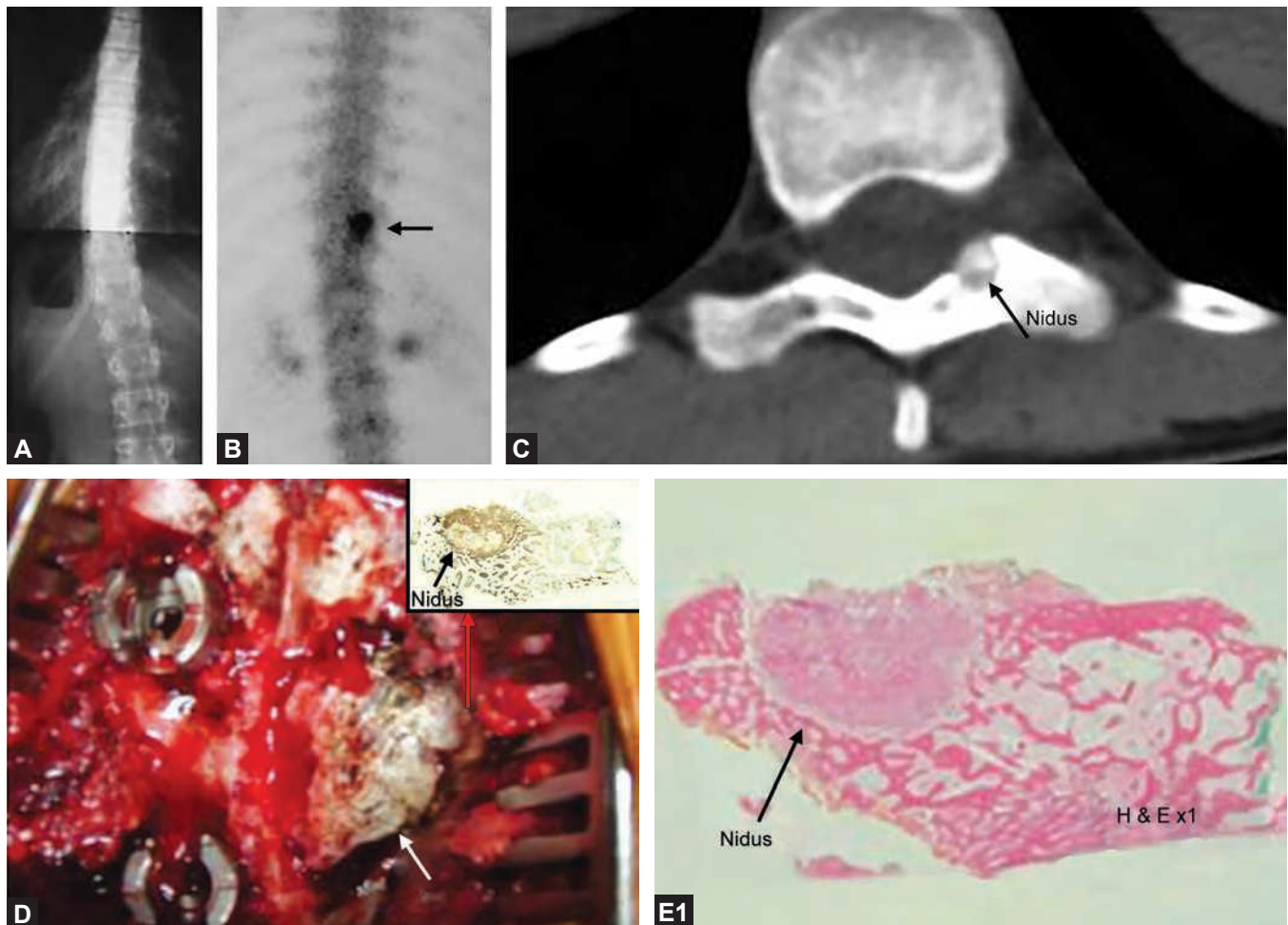
have been successfully treated with nonsteroidal anti-inflammatory drugs (NSAIDs) in an average of 33 months.²⁰ However, the side effects of prolonged NSAID use, such as gastrointestinal bleeding, should be considered. Moreover, associated spinal deformity such as scoliosis will typically resolve spontaneously if the nidus is surgically resected within 15 months from the onset of deformity.¹⁴

Osteoblastoma

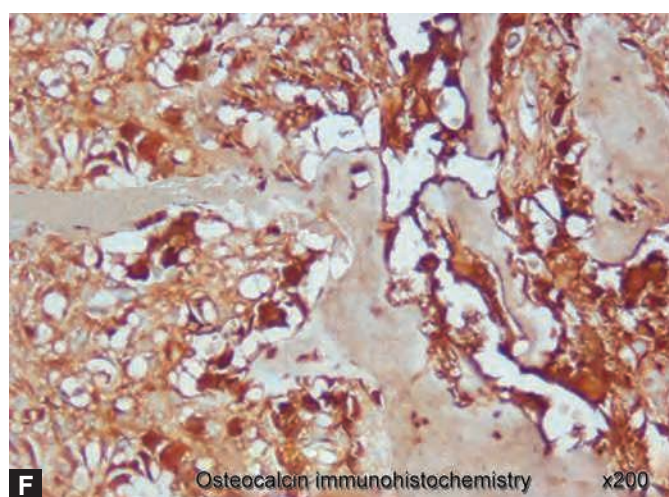
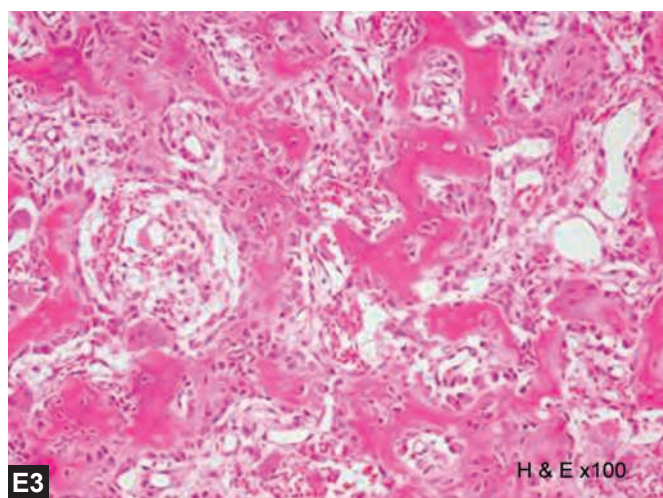
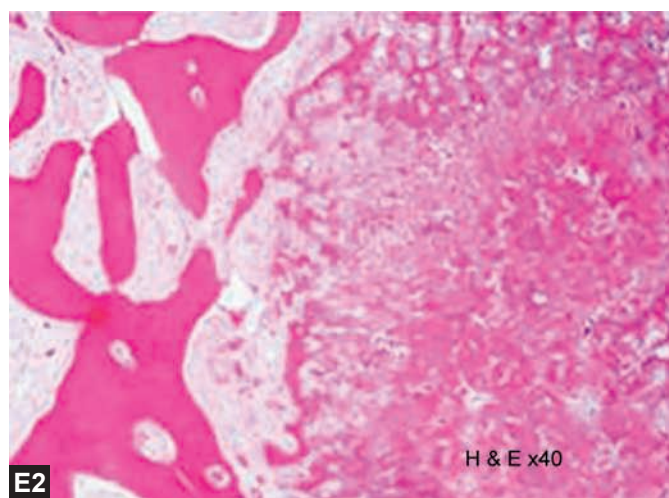
Osteoblastoma is a benign bone-forming tumor that is pathologically similar to osteoid osteoma except in that it is much larger and more aggressive in behavior. Osteoblastoma is rare, accounting for 1–3% of all benign bone tumors. Patients usually present in the second to the third decades of life. There is a male predilection with an M:F ratio of 2.5:1. The average age at presentation is 20–24 years, but

the age of onset has been reported to range from 1 to 72 years.²¹ Patients typically present with dull pain that gradually worsens. Symptoms are typically not worse at night and respond poorly to NSAIDs. Painful scoliosis is the common symptom, but is reported less frequently than in osteoid osteoma. Neurological deficits are reported in 32% of cases. For spinal osteoblastoma, 32–46% occur in the thoracic and lumbar spine, 9–39% in the cervical spine and 17% in the sacrum. It often involves the posterior column and may extend to the vertebral body in larger lesions.²²

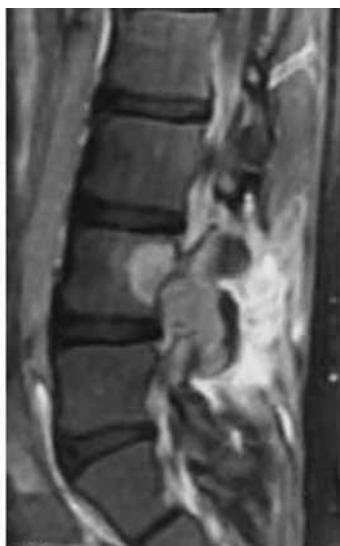
Radiographic features include a wide range of patterns. Lesions are >2 cm in size, predominantly lytic with a sclerotic rim, and expansile (Figs. 117.9A to D), sometime present with internal calcification. These lesions are very often associated with hypervascularity. Histologically, osteoblastoma is similar to osteoid osteoma, with prominent osteoblasts that produce woven bone (Figs. 117.9E and F).



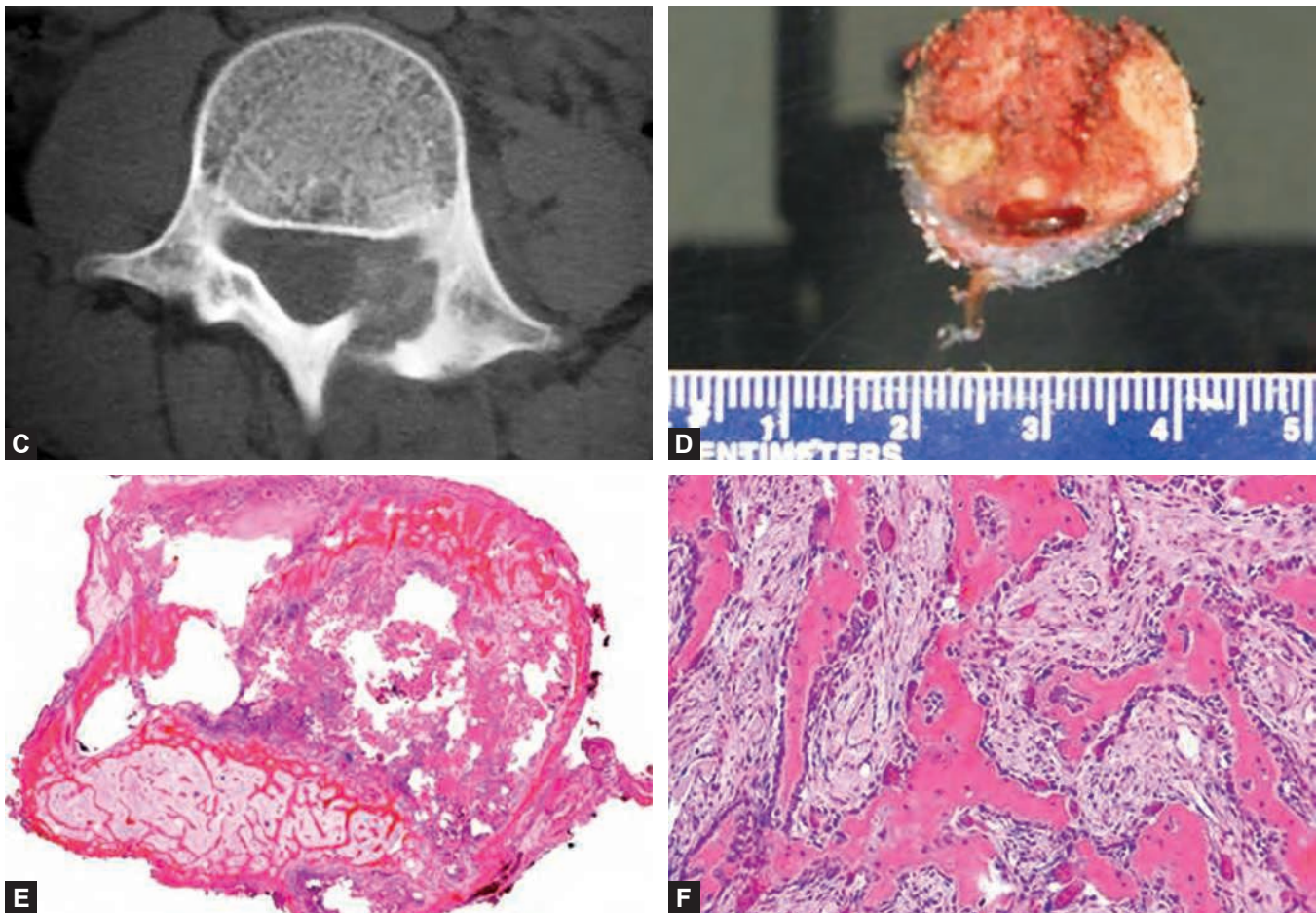
Figs. 117.8A to E1



Figs. 117.8A to F: Osteoid osteoma of the thoracic spine. (A) Anteroposterior radiograph showing thoracolumbar scoliosis. (B) Anterior view 99 m-TcMDP bone scan showing the area of increased tracer uptake is the left portion of T10 vertebra. (C) Computed tomography scan axial view showing the nidus (1 cm) can be seen at the lamina, with reactive sclerosis of the pars interarticularis and superior articular process and marrow edema extending up to the pedicle. (D) Intraoperative finding showing hypersclerosis of the tumor on the left posterior arch. (E) Hematoxylin and eosin showing the characteristic anatomosing bony trabeculae and osteoblastic rimming. (F) Osteocalcin immunohistochemistry showing positivity of osteocalcin immunohistochemistry reassures an osteoblast-rich lesion.



Figs. 117.9A and B



Figs. 117.9C to F

Figs. 117.9A to F: Osteoblastoma of the lumbar spine. (A) Sagittal magnetic resonance T1 and T2 weighted showing the intermediate signal activity of the osteoblastoma in the L4 vertebral body with minimal protrusion out into the vertebral canal posteriorly. Note the very bright high-signal aneurysmal component to the osteoblastoma extending out into the paraspinal muscle. (B) and (C) Serial axial computed tomography showing the lesion locates in the lamina and pars interarticularis, extends to superior articular process, and erodes spinal canal. (D) Gross pathology; shows well-defined, red to tan tumor mass with hemorrhagic areas. The compact tissue is granular and friable. Central nidus is >2 cm. (E) and (F). Hematoxylin and eosin showing irregular spicules of mineralized bone and eosinophilic osteoid rimmed by osteoblasts.

About 10–15% of osteoblastomas are associated with an aneurysmal bone cyst.

Wide en bloc surgical excision is the treatment of choice for osteoblastoma in cases of very painful lesions and lesions increasing size that can cause bony destruction, neurological compromise, and spinal instability. Pre-operative embolization is commonly performed to reduce the risk of intraoperative bleeding. If en bloc resection cannot be achieved due to limitations of the anatomic location, intralesional curettage and cementation or bone grafting may be performed.²³ Recurrence rates are reported to be 10–24%.²⁴ Intralesional excision has proven to be effective in Enneking stage 2 lesions and en bloc

resection in stage 3 lesions. Incompletion of the resection demonstrated higher recurrence rates.²³ Poor outcomes are generally due to malignant transformation to sarcoma, spinal cord compression and spinal cord necrosis.

Osteochondroma

Osteochondromas are relatively common in general, making up 9.2% of all primary bone tumors that are surgically treated. However, only 2.5% of all osteochondromas occur in the spine. They are cartilage-capped bony growths that typically occur in the cervical or upper thoracic spine. They are most often painless, but can be a source of pain, or very rarely spinal cord or nerve root impingement.²⁵

These tumors consist of expansile growths of cartilage-capped cortical bone with underlying medullary bone, with both types of bone being contiguous with their normal adjacent counterparts. Histologically, the tumor components are identical to those of normal bone. There is an M:F predominance of 2:1.^{26,27}

Approximately, 1% of osteochondromas will eventually undergo malignant transformation. If such a transformation is identified on tissue biopsy, or the patient is suffering from severe pain or neurologic deficit, complete surgical resection without neoadjuvant or adjuvant therapy is the treatment of choice.

Aneurysmal Bone Cyst

An ABC is a benign cystic lesion of the bone, the etiology of which is controversial. Features that lend weight to the theory that ABCs form as a reactive process include regression after removal and occurrence after fracture. However, the notion to categorize ABCs as a neoplastic disease is the discovery of the USP6 fusion gene (Tre2-oncogene) in ABCs.²⁸ The function of USP6 is still poorly understood but recent evidence has shown that USP6 is involved in endocytic trafficking and operates in a pathway that has been linked to mitogenic signaling and invasive behavior.²⁹ The lesions constitute 1.4% of all primary bone tumors and 15% of all primary spine tumors. Aneurysmal bone cysts are primarily seen in the second decade of life, with 20% occurring in patients <20 years old and a slight predominance in females. ABCs consists of blood-filled spaces that are separated by connective tissue containing trabeculae of bone or osteoid tissue and osteoclast giant cells. Out of all cases of ABC, 20–30% are located in the spine, especially the posterior elements, with extension to the vertebral body in 40% of cases. Nearly 70% of ABCs occur in the thoracolumbar region and 30–40% are associated with multiple, contiguous levels.³⁰

Plain films will typically demonstrate an expansile osteolytic lesion with a sharply defined border and thin sclerotic margins. Computed tomography reveals a characteristic multilocular lesion with cortical expansion. Magnetic resonance imaging shows multilocular lesions with fluid-fluid levels on T2 weighted images. Although these findings are highly indicative of ABCs, GCT, and telangiectatic osteosarcoma should be included in the differential diagnosis. Although they are often primary, one third of ABCs occur secondarily after other benign bone tumors, such as chondroblastoma, fibrous dysplasia, or GCT.

Histological findings are small blood-filled spaces separated by septae. This consists of spindle-cell fibrous tissue and multinucleated osteoclast-like giant cells with thin trabeculae of woven lamellar bone without an endothelial lining and thin wall blood vessels.

Aneurysmal bone cysts do not spontaneously resolve and surgical intervention is needed. Minimally invasive approaches consisting of selective arterial embolization have shown to promote regression and recalcification and provide symptomatic relief.³¹ Selected cases included patients who had intact lesion and without severe instability or neurological compromise.

In more aggressive lesion, surgical removal of the tumor is indicated. Intralesional curettage resulted in recurrent rate of 10–31%,^{30,32} while complete marginal resection showed recurrent rate of 10%.^{33,34} However, marginal or wide resection may not be possible due to the location of the lesion and possible postexcisional spinal instability. Preoperative embolization is suggested to reduce intraoperative blood loss in relatively large lesions. Adjuvants such as phenol, liquid nitrogen,³⁵ argon beam electrocautery,³⁶ and polymethyl methacrylate (PMMA)³⁷ may significantly lower rates of recurrence. The percutaneous injection of fibrosing agents has been used either alone or in conjunction with surgery, but the technique has been largely abandoned due to high rates of complications, such as pulmonary embolus, aseptic fistulization and transient inflammatory reaction.³⁸ Radiotherapy has been done in inoperable case; however, it is associated with a high rate of recurrence (31%)³⁹ and a risk of transforming into a sarcoma.

Giant Cell Tumor of Bone

Giant cell tumors comprise 18–23% of benign bone neoplasms and 4–9.5% of all bone neoplasms. Of all GCTs, approximately 2–5% occur in the spine.⁴⁰ Giant cell tumors are most often found in the vertebral body, with primary sites equally distributed between cervical, thoracic, and lumbar regions.⁴¹ They almost always occur after the growth plate has closed and are therefore typically seen in early adulthood, with 80% reported between the ages of 20 and 30 years. Females are affected with more frequency. Giant cell tumors are believed to result from an overexpression of the RANKL signaling pathway that leads to an uncontrolled production of osteoclasts.⁴² Back pain is the most common presentation complaint and may be accompanied by radicular pain. Spinal cord compression

and neurological deficits may be present in up to 50% of cases.⁴¹

Radiographs reveal an expansile, osteolytic lesion with a sclerotic rim.⁴³ Computed tomography and MRI provide a higher level of anatomical detail and demonstrate any invasion into adjacent tissue. Chest X-ray or CT is required to evaluate for rare cases of pulmonary metastasis. On gross pathology, GCTs are made up of yellowish-tan, soft, and friable tissue. Histologically, GCTs are composed of two cell types—osteoclast-type giant cells and spindle cells that are considered the active tumor cell. Giant cell tumors frequently coexist with aneurysmal bone cysts, resulting from numerous thin wall vascular channels that may cause hemorrhages.

En bloc excision with a wide margin is recommended for GCTs of the thoracic and lumbar spine or Enneking stage 3 tumors,⁴⁴ although a wide margin may be difficult to achieve and is associated with greater morbidity than intralesional or marginal excisions. In the cervical and sacral regions where a wide margin may be technically impossible, treatment is typically intralesional curettage and packing with bone graft or PMMA bone cement. Intralesional resection may provide adequate control with Enneking stage 2 tumors.⁴⁴ En bloc excision has a local recurrence rate of 20–25%⁴³ while intralesional curettage has shown recurrence rates of 40–60%. There were more frequent recurrences in patients who had a lesion involving both the arch and body of the vertebra.⁴¹ Intraoperative adjuncts such as cryotherapy, cauterization or chemical treatment such as phenol and hydrogen peroxide have lowered the recurrence rates to 2.5–10%.⁴⁵ However, Ruggieri et al. reported that adjuvants had no influence on local recurrence for sacral GCT.⁴⁶ Adequate removal of the tumor by curette and high-speed burr is the most important factor to achieve good outcomes.⁴⁷ Age <25 years⁴⁴ and >45 years⁴⁸ has been associated with shorter relapse-free survival in spinal GCTs.

Single or multiple uses of intravenous bisphosphonates with subsequent complete surgical resection could reduce the recurrence rate of GCT.^{49–51} In small series, the direct RANKL inhibitor denosumab has shown great promise in its ability to decrease GCT size and induce new bone formation among patients with unresectable GCTs.⁵² However, further randomized trials with higher enrollment and long-term follow-up are needed before this therapy becomes mainstream.⁵³

Hemangioma

Often discovered incidentally, hemangioma, a type of vascular abnormality, may develop along the axial spine. While <5% of patients with a spinal hemangiomas develop symptoms, they may be the cause of significant neck or back pain when the growth causes spinal cord or nerve root compression, compression fractures, or rarely an epidural hemorrhage.² If a spinal hemangioma is causing pain alone, with no neurologic deficit, analgesia can typically be achieved without undergoing surgery. However, if an expansile hemangioma causes progressive neurologic deficit, surgical decompression is recommended. Expansion of hemangiomas to the point of causing spinal cord compression has been reported during pregnancy.

Within the involved vertebrae, plain radiography and CT typically will demonstrate coarsened trabeculae with a characteristic “honeycombed appearance,” while MRI typically demonstrates a soft tissue component.

When intractable pain or neurologic deficit is present due to a spinal hemangioma, the anatomic location is amenable to excision, and the patient is a suitable surgical candidate from a medical perspective. The ideal treatment is laminectomy followed by adjuvant radiation therapy, which has been shown to yield a 93% rate of neurologic recovery without recurrent symptoms in a 52-month follow-up period, while laminectomy alone resulted in local tumor control rates of 70–80%.^{54,55} Percutaneous vertebroplasty should be considered in patients who have symptomatic hemangiomas who are not good surgical candidates, as this less invasive treatment has been shown to result in excellent pain relief.⁵⁶

Eosinophilic Granuloma (Langerhans Cell Histiocytosis)

Eosinophilic granulomas are the bony tumors associated with Langerhans cell histiocytosis. They are most commonly found in children <10 years of age, and vertebral involvement is found in 10–15% of these cases.²⁵ They are typically benign, destructive lesions caused by a proliferation of histiocytes. These tumors are most often self-limiting, and occasionally affect multiple spinal levels. Usually found incidentally, they are rarely the cause of significant pain.

Radiographically, eosinophilic granulomas are identified as destructive, lytic lesions with clearly demarcated borders and no soft tissue involvement. Adjacent disc spaces are well preserved. These lesions must be differentiated

from other lytic lesions, such as infections or malignancies.

These lesions will typically resolve over time, so conservative treatment with bracing and limiting activity is the best initial approach. However, if lytic destruction causes vertebral collapse and neurologic compromise, surgical decompression and arthrodesis may be required.

MALIGNANT TUMORS

Primary malignant tumors of the spine account for <5% of primary bone tumors.³ The most common bone sarcomas are osteosarcoma, chondrosarcoma, EWS, chordoma, and malignant fibrous histiocytoma/fibrosarcoma.³ Surgery is the mainstay of treatment, although the anatomy of the bony spine and its relation to the spinal cord often limits complete surgical resection with wide margin. Chemotherapy and radiation therapy have shown variable effects on these tumors. With recent advances in surgical techniques and development of new chemotherapy, local control and patient survival are improving.

Osteosarcoma

Spinal osteosarcoma accounts for 3.6–14.5% of primary spinal tumors^{57,58} and 1.2–3% of all osteosarcomas.^{59,60} It occurs more commonly in older age groups than osteosarcoma of the extremities, at a mean age of diagnosis of 38 years.⁶⁰ There is a slight predominance in females over males. Eighty percent of vertebral osteosarcomas develop in the posterior elements. Pain in the area of involvement is the first symptom in most patients. Fifty to seventy percent of patients display neurological symptoms.⁶⁰

Plain radiographs show cortical destruction and soft tissue mass formation. Osteoid matrix can be seen in most cases. Lesions may show osteolytic or osteoblastic features. Magnetic resonance imaging is superior for demonstrating tumor extent within the bone marrow and any associated soft tissue masses, including the delineation of epidural tumor extension.

Complete resection with neoadjuvant and adjuvant chemotherapy is the mainstay of treatment. Common therapeutic medications include cisplatin, methotrexate, and doxorubicin.

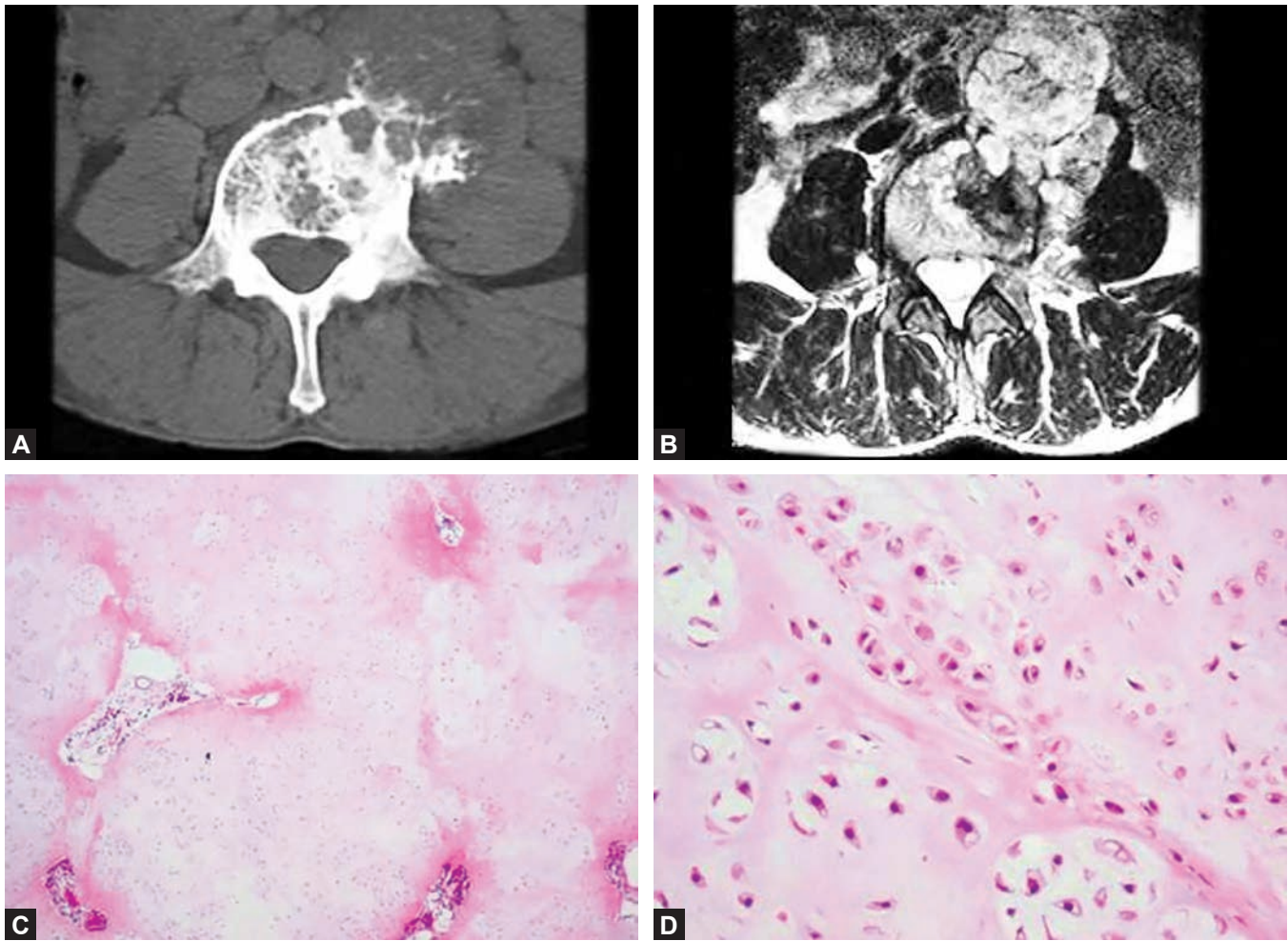
Based on data from the SEER registry,³ median survival in patients with an isolated lesion of primary osteosarcoma of the spine was 18 months compared to 7 months in those who present with distant metastasis. Ozaki et al.³⁷ studied 12 patients with spinal osteosarcoma and showed overall

survival had decreased in patients with distant metastases, tumors larger than 10 cm, and sacral tumors. Wide or marginal excision of the tumor improves survival. Shives et al.⁶⁰ showed only 1 in 30 patients survived for > 10 months. The prognosis is worse when compared to appendicular tumors because of the increased challenges to performing wide excision without injury to the surrounding vital structures. Patient outcomes are difficult to compare due to the use of different treatment protocols of varying chemotherapy and resection techniques in different treatment centers. Bisphosphonates have been used in conjunction with chemotherapy in osteosarcoma of the extremities and showed no significant improvement in 5-year and overall survival (72%, 93%), but may improve the durability of instrumentation.⁶¹ Mifamurtide, an immune-stimulant muramyl tripeptide phosphatidylethanolamine, was used in clinical trials of 677 patients in adjunct with chemotherapy and showed an improved overall survival, but did not reach statistical significance in event-free survival.^{62,63} Another immunotherapeutic agent that is being pursued for pulmonary metastatic disease is inhalation of aerosolized granulocyte macrophage colony-stimulating factor. However, a benefit could not be shown in a trial of 43 patients with pulmonary relapse and it should not be considered a standard therapy.⁶⁴

Chondrosarcoma

Chondrosarcoma is a malignant cartilaginous tumor that accounts for 20–27% of all malignant bone tumors. Typical presentation is in the 4th and 5th decades. There is a slight male predominance. Male:female is 1.5–2:1 for chondrosarcoma in general, and spinal chondrosarcoma has an even greater male predominance of 2–4:1. Chondrosarcoma occurs in the spine in approximately 2–12% of cases,⁶⁵ affecting the thoracic spine the most (51%), followed by cervical (35%), and lumbar segments (14%).⁶⁶ Posterior elements and the vertebral body are affected in 45% of cases, the posterior elements alone in 40%, and the vertebral body alone in 15% of cases.⁶⁷ In general, the patient often presents with pain and a large mass at the time of diagnosis. About 50% of the patients present with neurological symptoms.⁶⁷

Radiographic findings of chondrosarcomas depend on the histological grading. Most low-grade tumors demonstrate lytic lesions on imaging, which may be difficult to differentiate from enchondroma. High-grade tumors demonstrate moth-eaten destruction with “ring and arc” (Figs. 117.10A and B) or popcorn calcification and



Figs. 117.10A to D: Chondrosarcoma of the spine. (A) Axial computed tomography scan showing a large mass arising from the vertebral body with cortical disruption and “ring and arc” calcifications. (B) Axial T2-weighted magnetic resonance showing a high-signal intensity lobulated mass with linear striations. (C) and (D) Photomicrograph (original magnification, x4 and x40, hematoxylin and eosin stain) showing a lobulation of cartilage tumor and resorption of the pre-existent bone trabecula (C) and low-to-moderate cellular atypia and mitotic activity, demonstrated by hypercellularity, binucleate cells, multiple cells in lacunae and atypical nuclei.

endosteal scalloping. Histological grading is the best predictor of the prognosis (Figs. 117.10C and D).

Chondrosarcomas are generally resistant to radio and chemotherapy; therefore, surgical removal is mandatory. Surgical treatment varies with grading and location; most grade 1 lesions can be treated by curettage (90% 5-year survival) and grade 2–3 with wide excision (29%, 5-year survival).

En bloc resection with a wide margin provides the best results regarding tumor control, with reported rates of recurrence of 3–8%.⁶⁸ In contrast, an intra-lesional curettage shows recurrence rates of up to 100%.^{68,69} Recurrence usually occurs within 3–5 years postoperatively, and earlier if a subtotal excision had been performed. Tumor-related

death is estimated at 12% in patients who undergo subtotal resection, compared to 42% in patients who undergo wide excision with a clear surgical margin.^{70,71} Although en bloc resection with clear margins is the ideal surgical management for spinal chondrosarcoma, the achievement of this may be technically challenging.

Chemotherapy has not proved to affect the outcome in spinal chondrosarcoma; therefore, its role is limited.^{68,69} The ineffectiveness of chemotherapy may be explained by tumor cells’ expression of multidrug resistance gene, P glycoprotein, large amounts of extracellular matrices in the tumors, or the poor vascularity and the low proliferation rates of chondrosarcomas.⁷² New chemotherapeutic agents such as histone deacetylase and aromatase

inhibitors are being studied in patients with unresectable or metastatic disease, but not enough data are currently available to determine whether these should be used on a more widespread basis.

Radiotherapy is frequently used in patients with surgically inadequate margins, but the overall survival in this group is lower than those who had margin-free en bloc excision without radiation.^{68,73}

Ewing Sarcoma

Ewing sarcoma is the second most common primary bone tumor, and typically occurs in children and adolescents between the ages of 10 and 20 years. It has a male predilection (M:F, 1.5:1). Ewing sarcoma is a small blue round cell tumor that is closely related to primitive neuroectodermal tumor (PNET), Askin tumors, and neuroepithelioma, all collectively are referred to as the Ewing sarcoma family of tumors. They share similarities in microscopic appearance and nonrandom t(11;12)(q24;q12) chromosome rearrangements. Up to 13% of EWS occurs in the spine that affects the sacrococcygeal (54%) and the lumbar regions (25%) most commonly.⁷⁴

Histological findings can be confused with osteomyelitis or hematologic malignancies, but EWS round cells are significantly larger than lymphocytes. Mitotic figures are present intermittently with karyopyknotic cells and apoptotic cells. Immunohistochemical staining of CD99 and vimentin is positive. CD99 positivity is due to the glycoprotein product of the *MIC2* gene, which is a common finding of EWS and PNET tumors. Ewing sarcoma does not produce matrix. It does, however, often produce large soft tissue masses that invade adjacent structures as well as the epidural space.⁶

Neoadjuvant chemotherapy with or without radiation is indicated for EWS. Ewing sarcoma responds more favorably than other bone sarcomas to radiation therapy, resulting in a nearly twofold increase in the 10-year survival rate since the 1980s. Survival prognoses of patients with EWS of the spine are slightly better than that of patients with spinal osteosarcoma. Patients have a median survival of 90 months in the case of an isolated lesion and 20 months in the case of metastatic disease. The overall 5-year survival rate is approximately 41%.⁷⁵

Chordoma

Originating from primitive remnants of the notochord, chordomas tend to be extremely difficult to resect due to

their proximity to neural elements. Data from the SEER registry indicate an annual incidence of 0.08 per 100,000 people. The M:F ratio is roughly 2:1, and patients tend to be >40 years of age.¹ Studies vary in reports of distribution in the axial skeleton; some studies show a propensity for distribution in the sacrococcygeal area and skull with a minority in the mobile spine, while others show a roughly even distribution between these three areas.^{76,77} Non-specific back pain is present in nearly all patients, with a radicular component in a minority. More than two-thirds of patients present with neurologic deficits. When the tumor arises in the sacrum, rectal dysfunction such as constipation, obstipation, or hemorrhoidal bleeding is common, and the tumor may be palpable on rectal examination.

Grossly, chordomas appear lobulated, gray, and partially translucent. Calcification may be identified by plain radiographs, but CT and MRI are most helpful in distinguishing bony and soft tissue extension, respectively. There is generally a tumor pseudocapsule. Histologically, chordomas are made up of “soap bubble” cells or “physaliferous cells” with vacuolated cytoplasm, as well as signet ring cells.

The optimal treatment for chordomas is wide en bloc resection, though this may be technically difficult to achieve as neural structures are typically involved. Regardless, a wide resection should be attempted while sparing as many nerve roots as possible. In the sacral area, sparing at least one of the S3 nerve roots may be sufficient to spare urinary and fecal continence. Local recurrence rates are high, particularly if the tumor’s pseudocapsule is violated, in which case local recurrence was identified in 64% of patients in one study.⁷⁸ Chordomas are generally not radiosensitive, and conventional external beam radiation is of limited or no value in their treatment, but newer modalities such as photon or proton beam therapy are now often employed as adjuvant therapy in an effort to reduce or delay recurrences. Radiotherapy is also offered for palliative, subjective pain control. As of yet, there is limited objective data as to the effectiveness of these strategies. Chordomas are similarly chemoresistant in general, but patients are often started on chemotherapeutic agents after receiving maximum radiation dosages or in cases of metastasis. Combinations of adriamycin-cisplatin or ifosfamide-adriamycin-platinum have shown some limited success. Recently, a number of investigators have seen good responses when treating chordomas with tyrosine kinase and angiogenesis pathway inhibitors, such as imatinib (Gleevec), erlotinib (Tarceva), and gefitinib (Irlissa).⁷⁹⁻⁸¹

More higher-enrollment, long-term studies are necessary to determine the long-term efficacy of these specific inhibitors.

Plasmacytoma/Multiple Myeloma

Solitary plasmacytomas of the spine and multiple myeloma may be thought of as two diseases on a spectrum, characterized by infiltration of the bone marrow by malignant plasma cells. Multiple myeloma is the second most common hematologic malignancy after non-Hodgkin's lymphoma, and is further characterized by multiple bony lesions as well as a marked reduction in normal immunoglobulins coupled with overabundant monoclonal antibodies in the serum, urine or both, in 99% of patients. Solitary plasmacytomas occasionally remain truly localized, and patients may remain disease-free after local radiation therapy, but in one half to two thirds of patients, plasmacytomas ultimately progress to multiple myeloma.^{1,82} These tumors cause osteolysis and when advanced may lead to vertebral collapse and subsequent myelopathy. In multiple myeloma, but rarely in the case of a truly solitary plasmacytoma, a monoclonal immunoglobulin spike is easily detected on serum or urine protein electrophoresis. Median survival in patients diagnosed with multiple myeloma is 28 months, while median survival of patients with solitary plasmacytoma exceeds 5 years.

Plasma cell tumors are highly radiosensitive. In the case of a solitary plasmacytoma, in the absence of spinal instability or neuropathy, local radiation alone is the treatment of choice, and this can be expected to achieve long-term control if not cure. Radiation therapy is also a key component when multiple myeloma is diagnosed, but bisphosphonates should be added to reduce excessive bone loss and pain. When large lytic lesions are obvious on imaging, patients with either diagnosis should be offered percutaneous vertebroplasty as this confers almost instantaneous pain relief in > 80% of patients.^{83,84} This may be offered even before radiotherapy, as it is immediately palliative for the patient and may prevent postradiation segmental instability or compression fractures. Instrumentation is generally necessary for stabilizing the spine if > 50% of the involved vertebral bodies have been eroded. In recent years, immunomodulatory treatments such as thalidomide and dexamethasone, proteasome inhibitor bortezomib (Velcade), and direct RANKL inhibitor denosumab have shown great promise in treating patients with multiple myeloma and further studies may lead to more widespread, efficacious treatments in the future.

Lymphoma

Hematologic malignancies originating from the spine most often occur in children. The patients may present with compression fractures in 5.7–16% of cases.⁸⁵ Tumors from both leukemia and lymphoma are most commonly found at the mid-thoracic or thoracolumbar level. Tumors can extend into the epidural space, resulting in neurological symptoms. Early diagnosis is mandatory because generally the prognosis is good when the proper treatment is initiated early. Treatment consists of chemotherapy with or without radiation, and surgery is generally not indicated.

Histological findings include densely packed lymphoid cells within the marrow space. Non-Hodgkin lymphoma presents as sheets of large B-cell with CD20 positivity. Hodgkin lymphoma has a heterogenous collection of hematopoietic cells, including Reed-Sternberg cells that are positive for CD15 and CD30.

SUMMARY

Primary bony spinal tumors, whether benign or malignant, are relatively rare. Nevertheless, whenever a patient presents with ongoing back pain, particularly if it is nocturnal, and/or the patient suffers from progressive neurologic deficits, the clinician must always rule out a spinal malignancy.

Definitive diagnosis and management of spinal tumors should be performed at a musculoskeletal oncology referral center. A cooperative, multidisciplinary team approach is essential to achieving the best outcomes. With the development of targeted therapies based on an improved understanding of the molecular pathology of spinal tumors, as well as with advances in diagnostic imaging, surgical technique, and percutaneous treatments, functional and survival outcomes of patients with spinal tumors may be expected to continue to improve in the future.

KEY POINTS

- Primary bony spinal tumors are rare, but deserve consideration in any patient presenting with back pain of uncertain etiology and must certainly be considered in any patient presenting with progressive neurologic deficits.
- Whenever possible, management of spinal tumors should be handled at all stages by a multidisciplinary team at a higher-level institution with extensive

experience in spinal oncology, as this has been shown to reduce rates of complications during treatment as well as tumor recurrence and overall survival statistics.

- All spinal tumor diagnoses should be confirmed by histology. Appropriate oncologic (Enneking) and surgical (WBB) staging must be assessed before deciding on a course of treatment.
- En bloc excision with a wide margin is typically the surgical treatment of choice, but is not always feasible given the unique anatomy of the spine and the need to retain neural structures.
- Percutaneous techniques such as RFA and vertebroplasty are being used ever more often for palliative, and at times definitive, curative treatment for bony spinal tumors.

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Tumors of the Sacrum

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Snapshot

- » Sacral Anatomy
- » Epidemiology and Clinical Presentation
- » Staging
- » Surgical Planning
- » Resection Techniques
- » Reconstruction Techniques
- » Complications

INTRODUCTION

Sacral tumors are challenging neoplasms to treat, given their anatomic proximity to major vasculature and neural elements that control ambulation, sphincter control and sexual function. Primary sacral tumors are rare, representing only about 1% of all primary bone tumors and 7% of all primary spinal tumors.^{1,2} Because these tumors typically expand anteriorly and usually do not cause palpable posterior masses, they are often not discovered before reaching a large size and causing substantial osseous destruction.^{2,3} Although surgical resection and reconstruction techniques for sacral tumors have improved, new therapies are emerging and evidence-based algorithms for treating these tumors remain to be thoroughly developed and tested.

SACRAL ANATOMY

The adult sacrum consists of five fused vertebrae. Ossification of the intervertebral discs occurs in late adolescence through the third decade of life. The anterior surface of the sacrum is concave, and the posterior surface is convex; in addition, the sagittal tilt of the pelvis relative to the pelvis and acetabuli is variable. Understanding these unique anatomic features is necessary to evaluate radiographic studies of the sacrum in cases of suspected neoplasms and

plan surgical resections. In adults, the dural sac generally terminates at S2.⁴ There are four pairs of ventral and four pairs of dorsal foramina to allow the anterior and posterior divisions, respectively, of the sacral nerve roots to exit the sacral canal. Important for sacral resections, the piriformis muscles originate on the anterolateral aspect of the sacrum; posteriorly, the gluteus maximus, erector spinae and multifidus muscles all attach.⁵

EPIDEMIOLOGY AND CLINICAL PRESENTATION

Initial clinical findings of sacral tumors typically include localized pain, often mimicking lumbar spondylosis. Neurologic findings can occur as the tumor increases in size and include lower extremity radicular pain, perineal pain and numbness and bowel/bladder dysfunction. These neurologic symptoms can sometimes be exacerbated with a Valsalva maneuver. Reflex exam can reveal diminished Achilles reflexes due to S1 involvement or absent bulbocavernosus and anal wink reflexes. Rectal exam can sometimes reveal a palpable mass in the presacral space, and bowel obstipation from rectal compression is another frequent presenting symptom of sacral tumors.^{6,7}

The differential diagnosis for sacral tumors is summarized in Table 118.1. Metastatic lesions are the most

Table 118.1: Differential diagnosis of sacral tumors.

<i>Benign</i>	<i>Malignant</i>
Giant cell tumor	Metastasis
Osteoid osteoma	Chordoma
Osteoblastoma	Ewing sarcoma
Aneurysmal bone cyst	Osteosarcoma
Schwannoma	Chondrosarcoma
Neurofibroma	Multiple myeloma
Myxopapillary ependymoma	Lymphoma
Osteomyelitis	Invasive colorectal tumor

common sacral tumors, accounting for slightly more than 50% of all sacral neoplasms. An estimated 18% of all sacral lesions are primary malignant tumors, and 29% are primary benign lesions; however, these percentages can vary between series.⁸ Primary sacral tumors account for 1–7% of primary spinal neoplasms.⁹ Chordomas are the most common primary sacral neoplasm, representing 36–44% of all primary sacral neoplasms and 50% of malignant primary sacral tumors.^{8–11} While varying in frequency in the literature, chondrosarcoma, osteosarcoma and Ewing’s sarcoma all occur with some frequency in the sacrum; sometimes the sacrum is the site of origin, and in other cases the tumor extends into the sacrum after originating in the posterior ilium.^{9,12}

Giant cell tumors (GCTs) are the second most common primary sacral tumor after chordomas, and the most common benign sacral lesion; they represent approximately 2–13% of all primary sacral tumors and 71% of benign sacral tumors.^{7,9–11} Osteoid osteomas account for 9% of benign sacral tumors, and typically present with night pain relieved with anti-inflammatory medications. While they are rare bone tumors, more than 20% of osteoblastomas are found in the sacrum.¹² Sacral aneurysmal bone cysts (ABCs) are relatively rare, accounting for 1–2% of sacral tumors and between 2% and 13% of spinal ABCs.^{9,12–14}

Diagnosis

Imaging

Plain pelvic radiographs are often inconclusive studies of the sacrum due to overlying soft tissue and bowel gas, frequently leading to delayed diagnosis of sacral tumors.¹⁵

Blurring or obliteration of the sacral foramina is frequently caused by tumor growth. In a normal sacrum, foraminal struts should be distinctly seen, and the posterior iliac wing should be visualized as superimposed behind the sacral ala. Additionally, both the anterior and posterior margins of the sacroiliac joint should be identifiable, as this joint is oblique. If these structures cannot be delineated, then suspicion of possible sacral mass should be heightened.¹

Both computed tomography (CT) and contrast magnetic resonance imaging (MRI) scans are thus crucial to diagnosing and planning resections of sacral tumors.^{9,12,16} Chordomas are nearly always midline tumors, while GCTs are frequently eccentric.¹⁷ Both can erode into intervertebral disc spaces and the sacroiliac joints.^{12,17} Osteoblastomas typically arise in the posterior elements, often as lytic, expansile lesions surrounded by a sclerotic rim. Osteoid osteomas appear as sclerotic lesions with a nidus on CT and without soft tissue extension. ABCs typically display fluid-fluid levels on MRI; while these tumors typically arise in the posterior elements of the sacrum, most rapidly expand anteriorly into the vertebral bodies as well. Nerve sheath tumors (schwannomas and neurofibromas) can display a “target sign” on T2 MRI, in which a high-signal mass surrounds a low-signal center. As these tumors expand out of the sacral foramina, the foraminal borders are often obliterated on radiographs and the tumors assume a dumbbell shape on advanced imaging.^{1,9,17}

When a sacral lesion thought to be a neoplasm is identified, obtaining a radionuclide bone scan is useful to rule out polyostotic disease. Polyostotic findings limit the differential diagnosis, placing metastasis as most likely, with multiple myeloma, Paget disease, and vascular tumors as other possibilities.¹ To evaluate for visceral involvement or to track disease progress, positron emission tomography (PET) is another useful imaging modality.

Biopsy

Biopsies should be planned with direct consultation from the surgical team that will be performing any potential sacral resection. Biopsies can be done either open or with CT-guided core needle biopsy; the reported accuracy rate for pathologic diagnosis from sacral core needle biopsies is 92–100%.^{2,15} Biopsy sites should be placed so that the tract can be later excised with the surgical specimen, given that many sacral tumors are chordomas, which are known to readily seed adjacent tissues.^{15,18} Transrectal biopsies of sacral masses should be avoided.

STAGING

The Musculoskeletal Tumor Society (MSTS) staging system, originally developed by Enneking, separates benign and malignant tumors (Table 118.2). Benign lesions are staged with Arabic numerals (1, 2 and 3). Malignant lesions are staged with Roman numerals (I, II, III) and subdivided as A or B for intracompartmental or extracompartmental extent, respectively.¹⁹

The Weinstein-Boriani-Biagini (WBB) system was created specifically for spinal tumors. WBB staging communicates information regarding the extent and anatomic position of the subependymal giant cell tumors (SGCT) within the spinal column and is very useful in planning resection approaches (Table 118.2). The axial cross-section of the involved vertebra(e) is divided into 12 “pie slices” in a clock-face pattern; staging a tumor requires naming the slices which contain the lesion. In addition, the tumor is staged based on five concentric rings, designated A (extraosseous) to E (dural involvement).²⁰ Similarly, the Tomita system stages metastatic spinal tumors into seven categories based on location and extent of involvement (Table 118.2). Types 1–3 describe a location within the vertebral body, types 4–6 indicate extraosseous extension, and type 7 denotes multivertebral involvement.²¹

SURGICAL PLANNING

Surgical approach is dictated by tumor size and involved structures. Obtaining clean margins has been shown to be the single most important factor for minimizing the risk of recurrence, both for primary malignant and aggressive benign sacral lesions.^{2,22,23} Tumors without visceral extension can often be resected from a posterior-only approach, particularly if they are distal to S2.^{8,10,24} While many sacral tumors expand anteriorly, violation of the presacral fascia and direct involvement of the rectum does not occur.^{7,25} However, involvement of a colorectal surgical team is sometimes required during anterior dissections; the rectum can become adhered to the presacral fascia overlying the tumor, particularly if the area has received previous radiation. Primary colorectal tumors involving the sacrum also require a combined anterior/posterior approach.²⁴

Posteriorly, tumor infiltration into the gluteal and piriformis musculature does occur.⁷ After sacral resection, there is frequently a large void that may require reconstruction with biologic mesh and/or flap coverage to avoid posterior hernias.² Plastic surgeons should be included in preoperative planning, if a flap may be necessary.

Table 118.2: Summary of spine tumor staging systems.

Musculoskeletal Tumor Society (MSTS)/Enneking System

Benign

1	Well-demarcated lesion, contained within bone
2	Expansile lesion, cortical thinning
3	Soft-tissue extension, cortical breakthrough

Malignant

IA	Low-grade, intracompartmental
IB	Low-grade, extracompartmental
IIA	High-grade, intracompartmental
IIB	High-grade, extracompartmental
IIIA	Any grade, intracompartmental, metastasis
IIIB	Any grade, extracompartmental, metastasis

Weinstein-Boriani-Biagini (WBB) System

Tumor location noted as number (1-12) based on a clock face with spinous process positioned at 12 o'clock

Radial Layers

A	Extraosseous soft tissues
B	Superficial intraosseous
C	Deep intraosseous
D	Extradural
E	Intradural

Tomita System

Type

Intracompartmental	1	Vertebral body
	2	Pedicle
	3	Body and lamina
Extracompartmental	4	Epidural extension
	5	Paravertebral extension
	6	2–3 vertebrae
Multiple	7	>3 vertebrae

Neurologic sequelae of sacral resections can be debilitating and must be thoroughly discussed with patients prior to surgery. Bilateral L5 root preservation is necessary for ambulation, although a foot-drop orthosis is typically needed. Three in four patients with bilateral S1 root preservation after sacrectomy can ambulate more than 150 feet.^{10,26} Retaining both S2 nerve roots and sacrificing all distal roots can result in partial, but not normal, bowel/

bladder continence.^{2,25,26} A hemisacrectomy that leaves all roots intact on the contralateral side permits near-normal micturition and defecation.³ Patients with intact bilateral S3 roots retain bowel/bladder continence in 75–100% of cases, and approximately 50–70% of patients with unilateral S3 preservation are fully continent.^{10,23,26,27} Guo et al. identified bowel incontinence as a predictor of increased length of hospital stay ($P = 0.02$) and a cause of increased time to wound healing ($P = 0.03$).¹⁰ Impact of sacrectomy on sexual function is less well-described, but male patients who retain at least one S3 root are reportedly able to ejaculate while those with bilateral S3 root resection can achieve erection but have abnormal ejaculation. Hemisacrectomy does not substantially affect male sexual function. Females with S3-S5 bilateral root resections have reported normal sexual function, although this was determined from only two patients.^{3,26,28}

Sacral tumors often are hypervascular, with significant lumbosacral collateral circulation. Preoperative angiography should be done prior to sacral tumor resection, and embolization performed, if a tumor demonstrates significant vascularity.²⁹ Both internal iliac arteries, the median sacral artery, and other tumor-supplying arteries can be embolized, although embolizing both internal iliac arteries may predispose to a higher rate of posterior wound breakdown due to poor skin perfusion.^{2,30} Embolization using gelfoam or polyvinyl alcohol is temporary, and surgery should be performed within 24–48 hours after the embolization procedure to minimize recanalization.²⁹

Treatment

Chordomas

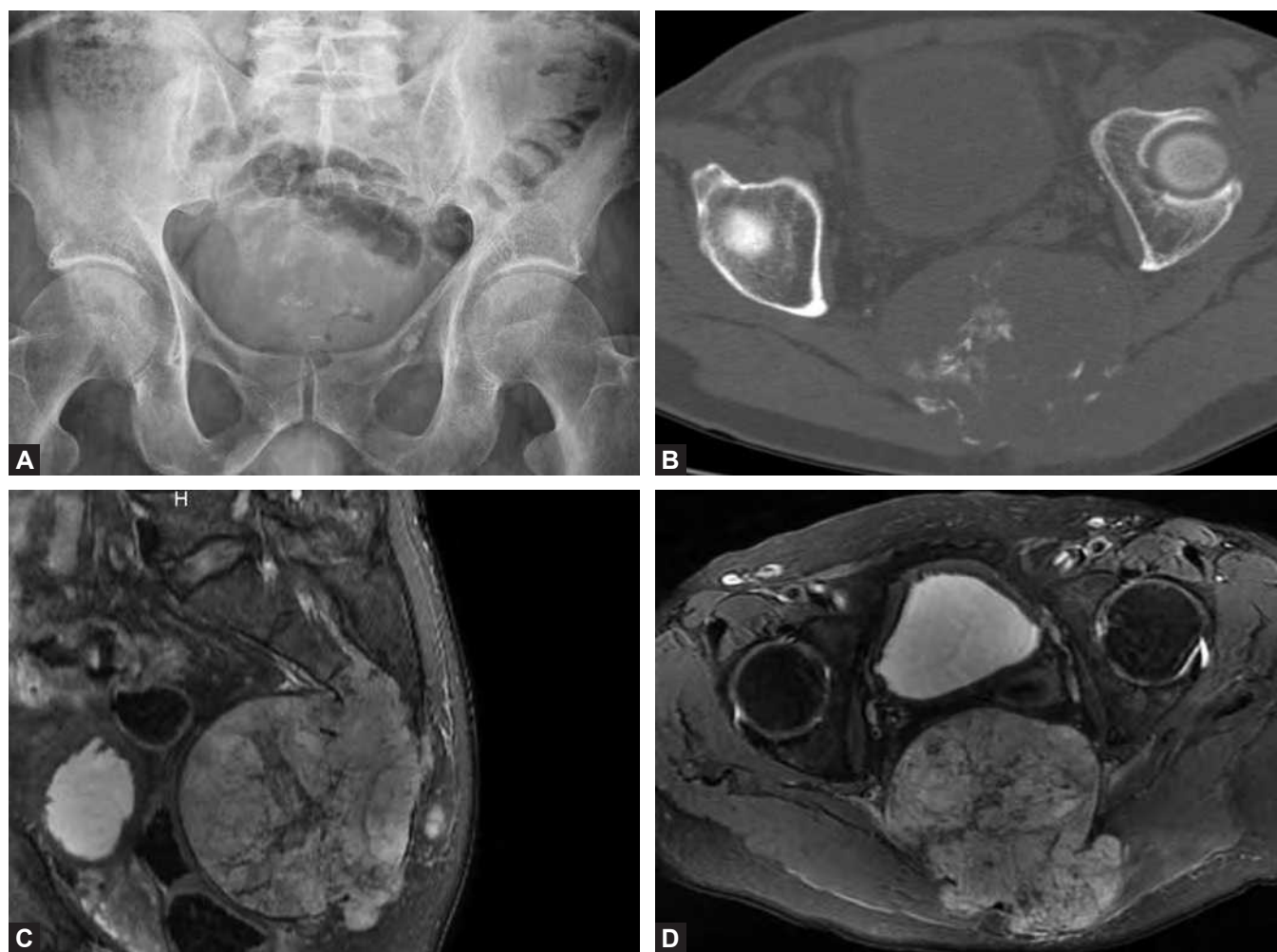
Chordomas are malignant tumors that originate from notochord remnants, accounting for 1–4% of malignant bone tumors. Half of all chordomas have been reported to occur in the sacrum; another 35% occur in the skull base (typically the clivus), and 15% are found in the mobile spine, although these percentages vary in different series.^{7,31–35} These tumors typically appear between ages 30 and 70, and the mean symptom duration prior to diagnosis has been reported as 2 years.^{7,33,36} Radiographically, a soft tissue mass can only be seen on radiographs in approximately 60% of cases, leading to delayed diagnosis in many cases (Figs. 118.1A to D). Calcifications within the tumor can be seen on radiographs in about half of chordoma cases, and on CT in almost 90% of cases.³⁷ Chordomas often invade

intervertebral disc spaces as well as the sacroiliac joint.¹² Histology reveals pathognomonic “soap bubble” physaliferous cells.³⁸ Dedifferentiated chordoma, a very rare form with histopathologic features of both chordoma and sarcoma, portends a more aggressive tumor with poorer prognosis.³⁹ Brachyury, a transcription factor which plays a central role in embryologic notochordogenesis, has been shown to be a reliable biomarker for chordoma. Identification of brachyury expression is often useful to histologically differentiate chordoma from mimics such as chondroid tumors and germ cell tumors.^{40,41}

Chordoma series have demonstrated a median survival after resection of 7.0–7.4 years, but with a wide range; some patients are alive more than 30 years after diagnosis.^{31,42} Five-year survival ranges from 45% to 86%, and 10-year survival varies from 28% to 60%.^{23,37,42–44} Longer survival has been significantly associated with obtaining wide surgical margins ($P = 0.0001$) and with younger patient age ($P = 0.04$).⁴³ Bergh et al. identified local recurrence as associated with a 21-fold increase in the risk of tumor-related death.³⁶

Local recurrence rates after resection also vary widely in the literature, ranging from 19% to 80%; approximately 19–30% of patients develop metastases, typically to the lungs.^{25,31,32,34,37,42,43,45–47} The mean time to metastasis has been reported as 4.2 years.⁴⁶ Intralesional resections have been reported to have double the recurrence rate than wide resections (64% vs 28%) and are a significant predictor of local recurrence ($P = 0.01$).^{42,45} The median disease-free interval after wide resection has been cited as 2.3 years, compared to just 8 months after subtotal resection ($P < 0.0001$). In subtotal resections, adjuvant radiation therapy (RT) improved the disease-free interval from 8 months to 2.1 years ($P < 0.02$).³¹ Chordoma extension into the sacroiliac joint, gluteus maximus and piriformis muscles has been shown to predict higher recurrence rates, and thus wider margins of these structures should be taken in these cases.⁴⁸ Postresection MRI should be done for surveillance every 3 months in the first year, every 6 months in the second year, and then annually.³⁸

Chordomas are relatively radioresistant, so RT is generally employed only in cases of contaminated margins or recurrences.⁴³ However, hadron RT (protons or carbon ions) has shown promise for obtaining improved results in chordoma control.^{49–55} Proton RT has demonstrated an added benefit of having minimal to no deleterious effect on patient quality of life during treatment.⁵⁶ These technologies are only available in a handful of tertiary centers,



Figs. 118.1A to D: Images from a 68-year-old male with a sacral chordoma, who presented with 3 months of low back pain, perianal numbness, and urinary incontinence. (A) A pelvic radiograph showed a large area of opacity overlying the sacrum with obliteration of the sacral foramina. (B) Axial CT demonstrated a large mass involving the sacrum with internal calcifications. (C) T2 MRI revealed that the tumor abutted S2; note that the rectum is being compressed but that the tumor has not violated the presacral fascia. (D) Axial T2 MRI demonstrated the posterior extent of the tumor, with infiltration into the gluteus maximus on the left; Surgical resection required a staged anterior/posterior surgery and achieved negative margins, with sacrifice of both S2 nerve roots. One year after his sacrectomy, he developed local recurrences in his ilium, and distant metastases to his lungs; he was started on palliative imatinib chemotherapy.

and larger clinical studies are still needed to determine how best to use these modalities to treat sacral chordomas. Hamamoto et al. effectively treated a recurrent sacral chordoma with palliative RFA when surgery, RT and embolization had failed to control the tumor.⁵⁷ Similarly, Kurup, et al. employed cryotherapy to treat five sacral/ischiorectal chordomas that had recurred after previous surgical resection.⁵⁸

Historically, chemotherapy has been largely ineffective against chordomas. However, new research has found that most chordomas over-express platelet-derived growth

factor receptor- β (PDGFR- β).⁵⁹ Imatinib is chemotherapy drug that specifically targets PDGFR- β , and has shown promising results against chordoma in initial trials.^{60,61}

Giant Cell Tumors

Sacral GCTs are benign but often aggressive tumors that can cause substantial bone erosion and neurologic impairment; however, GCTs can metastasize in 1–14% of cases, typically to the lungs.^{62–64} GCTs nearly always occur after skeletal maturity, in contrast to ABCs, which can have similar radiographic features to GCTs but typically occur

in skeletally immature patients.¹ Definitive treatment guidelines for sacral GCTs have not been established. In a literature review of 166 sacral GCT cases, Leggon et al. concluded that sacral GCTs had an overall recurrence rate of 48%, but that no patients who underwent wide excisions experienced recurrence.⁶⁵ Guo et al. treated 24 sacral GCT patients more conservatively, with intralesional curettage or partial excision. They reported an overall recurrence rate was 29%, with 70% of patients recurrence-free at 5 years. Mean time to recurrence was 13 months.²⁷ Boriani et al. provided evidence that en bloc resection of all MSTS/Enneking stage 3 spinal GCTs and intralesional resection of stage 2 spinal GCTs produces acceptable recurrence risk.⁶⁶

Li et al. reported the treatment of 32 sacral GCT patients. All patients underwent preoperative embolization. Patients then underwent wide resection ($n = 2$), marginal resection ($n = 11$), marginal resection plus curettage ($n = 12$), or curettage alone ($n = 7$). Curettage was supplemented with adjuvant ethanol application or argon beam coagulation. Twelve patients (37.5%) developed local recurrence, with the marginal resection group having a significantly lower recurrence risk than the curettage group (18% vs 71%, respectively; $P = 0.05$). These authors concluded that curettage alone should not be used to treat sacral GCTs, instead proposing a treatment algorithm based on GCT location within the sacrum. They argued that S3-S5 tumors should undergo en bloc resection, mid-line tumors should undergo proximal curettage (S1-S2 segments) and distal marginal resection (S3-S5 segments), and eccentric proximal tumors should undergo marginal resection with preservation of all contralateral nerve roots.⁶⁷ Intralesional resection of sacral GCTs can be augmented with cryoablation or argon beam coagulation.⁶⁸⁻⁷¹

In addition to surgical treatment, bisphosphonates and denosumab have shown effectiveness against GCTs as adjunct therapy when combined with surgery, or as stand-alone medical treatment for unresectable GCTs.^{23,67,72-75} Use of these medications both preoperatively and postoperatively should be considered. Also, serial arterial embolization has shown ability to control growth of sacral GCTs, improving pain and neurologic symptoms. Embolization should be considered as solo therapy in cases of unresectable or recurrent sacral GCTs, and is repeated at intervals of 4-6 weeks until symptoms improve and there are radiographic indications of decreased vascularity with reossification.^{9,29,76,77}

Radiotherapy has also been successfully utilized for unresectable sacral GCTs; however, the benefit must be

weighed against risk of sarcomatous conversion associated with the use of radiotherapy against GCTs.⁷⁸

Metastatic Disease

Sacral metastases are increasing in frequency due to longer survival in patients with advanced cancer. Primary management for metastatic bone disease is systemic treatment with chemotherapy for the primary tumor along with radiation for local control. Radiotherapy has been utilized for many years to treat metastatic bone disease and is considered frontline treatment with the primary benefit being pain relief.^{79,80} Another option for local control is open surgical treatment, which is typically invasive and morbid. Indications for surgery are pain palliation (typically after failure of other treatments), neurologic impingement, and instability.^{81,82} Several studies have demonstrated clear benefit of surgical decompression with or without radiation over radiation alone to maintain ambulation in patients with metastatic spinal cord compression.^{83,84} Feiz-Erfan et al. reported on 25 patients with sacral metastases who underwent surgical treatment. Despite a 40% complication rate, overall these patients did experience substantial pain relief.⁸⁵ Quraishi et al. found that 30% of patients undergoing urgent cauda equina decompression caused by a lumbosacral metastasis experienced at least one Frankel grade of neurologic improvement after surgery.⁸⁶

Newer techniques have expanded the treatment options for sacral metastases. Embolization of spinal metastases has demonstrated effectiveness in some studies when used as a solo treatment; most reported cases involve renal cell carcinoma (RCC). Kuether et al. embolized thoracic and sacral metastases in a single RCC patient who experienced neurologic improvement and tumor stabilization lasting at least 5 months.⁸⁷ O'Reilly et al. embolized spinal RCC metastases in 4 patients, noting improved neurologic function lasting for 12 weeks.⁸⁸

Percutaneous sacroplasty using polymethylmethacrylate (PMMA) cement has been shown in numerous series to reduce pain and improve ambulation in patients with tumor-related sacral insufficiency fractures.⁸⁹⁻⁹⁶ Nebreda et al. performed sacroplasty as well as cementation of the sacroiliac joint in a patient with a large S1-S2 metastatic lesion extending into sacroiliac joint who was experiencing intractable pain with weight-bearing.⁹⁷ One potential complication of sacroplasty is cement extravasation; tumor patients are at higher risk of this than patients with osteoporotic fractures because of the extensive cortical destruction often caused by lytic tumors.^{90,98} Cement extravasation

can catastrophically embolize to the pulmonary circulation or cause neurologic impairment.^{99,100} Moussazadeh et al. noted PMMA extravasation in more than 70% of sacroplasty patients, although none experienced any neurologic impairment.⁸⁹ Pereira et al. reported that 4 of 58 sacroplasty patients (7%) experienced neurologic deficits from cement leakage; two patients improved with observation, but two required surgical decompression.⁹⁰ CT-guided sacroplasty is preferable over fluoroscopy alone; CT better demonstrates cement leaks during injection and better visualizes sacral anatomy. Lateral fluoroscopic sacral views are complicated by the superimposed iliac wings.^{94,98,101}

Radiofrequency ablation (RFA) and cryoablation are two other percutaneous techniques for treating osseous sacral metastases. Use of RFA for bone metastases was first reported by Dupuy et al.¹⁰² and multiple series have demonstrated its effectiveness in the sacrum and mobile spine with minimal complications.¹⁰³⁻¹⁰⁶ Eighty percent of patients experience pain relief after the procedure, and patients frequently report pain improvement and activity increase up to 18–20 weeks post-procedure.¹⁰³ Nakatsuka et al. reported that 4 of 17 (24%) of patients treated with RFA for spinal metastases experienced neurologic damage, and that in all cases the tumor had disrupted the posterior vertebral body wall.¹⁰⁷ However, other studies have not described a complication rate this high. RFA can be combined with cement osteoplasty to stabilize lytic lesions after ablation, with good pain relief within 24 hours.¹⁰⁷⁻¹⁰⁹ Cryoablation can be utilized for osteoblastic or sclerotic lesions, as the increased bone density does not create impedance as with RFA. Use of CO₂ epidurography to create an insulating layer, as well as placement of a thermocouple to monitor the temperature surrounding the neural tissue, should be used to prevent inadvertent neurologic injury.¹¹⁰ Neuromonitoring is often utilized as well. As with sacroplasty, CT guidance should be used for these procedures. Lee et al. utilized a multimodal approach to a patient with a sacral RCC metastasis causing severe pain and lower extremity paresthesias. They first embolized and then cryoablated the tumor. Finally, they performed PMMA sacroplasty, and the patient's pain and neurologic impairment substantially improved within a week.¹¹¹

Aneurysmal Bone Cysts

In contrast to GCTs, ABCs are generally thought to not have metastatic potential. However, ABCs are often locally aggressive, causing substantial osseous destruction, pain

and neurologic impingement (Figs. 118.2A to D). As with GCTs, serial arterial embolization can be employed to treat ABCs nonsurgically.^{9,112,113} Boriani et al. retrospectively reviewed 71 spinal ABCs, 9 (13%) of which were sacral. Enneking stage 1 and 2 lesions were effectively treated with intralesional resection or serial embolization, while stage 3 lesions required en bloc resection to prevent recurrence.¹¹⁴ Similar to GCTs, denosumab has demonstrated promise for controlling and even shrinking spinal ABCs in small series, particularly in cases when embolization could not be performed because of vascular anatomy.¹¹⁵

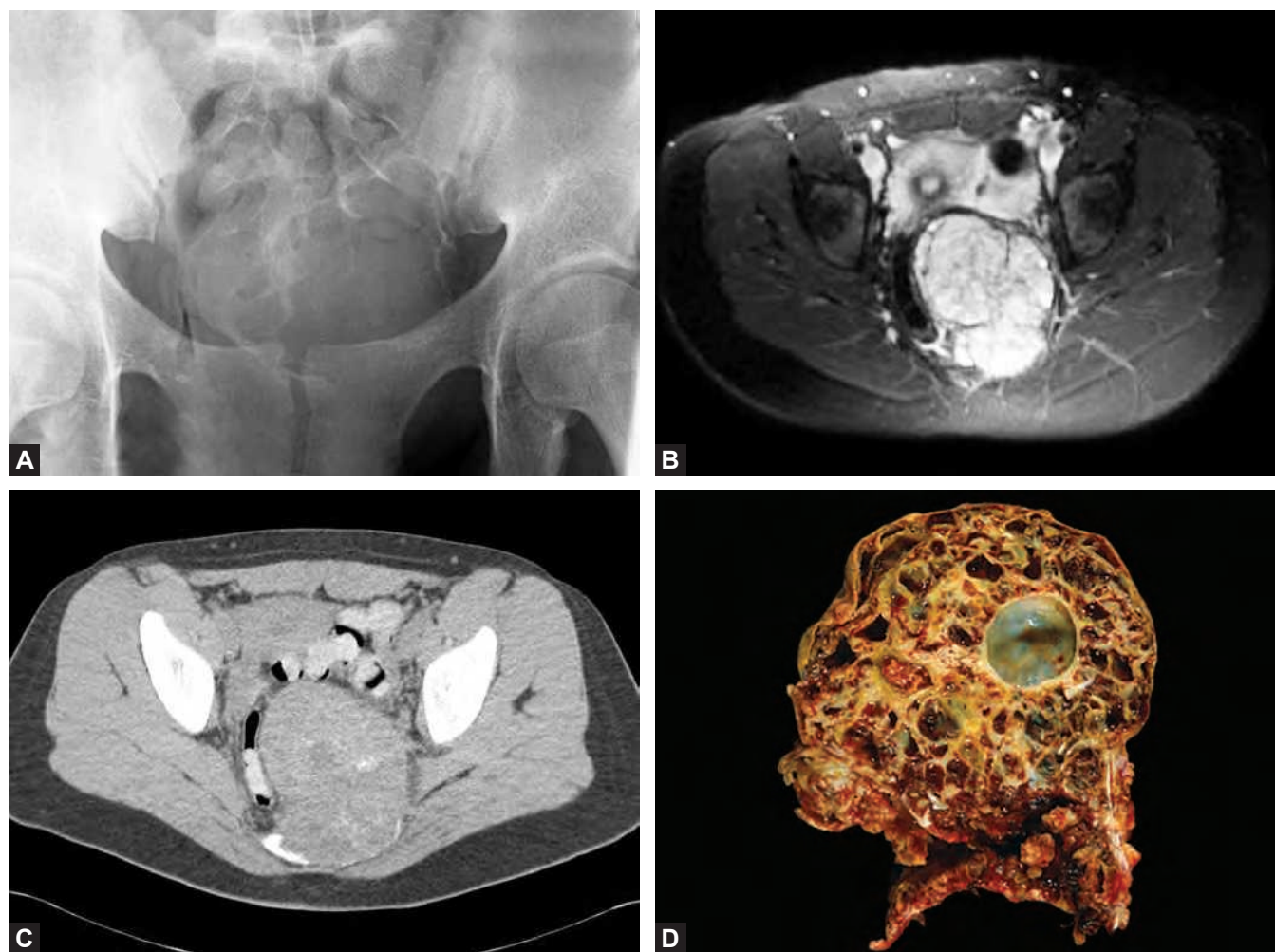
Nerve Sheath Tumors

Schwannomas and neurofibromas are both rare in the sacrum, although of the two schwannomas are much more common. Often these tumors present with neuropathic pain but without neurologic dysfunction, although they can also cause bowel/bladder dysfunction. While en bloc resection is the preferred treatment, nerve sheath tumors may have an intradural component and thus require intralesional resection. If the tumors involve the S1 or S2 roots, intraoperative nerve stimulation and electromyography (EMG) are essential during resection to minimize damage to nerve fibers.^{15,116} Several cases have also been reported in which stereotactic body radiation therapy (SBRT) has been utilized to treat sacral schwannomas effectively and without neurologic injury.^{117,118}

Ewing's Sarcoma and Lymphoma

Ewing's sarcoma and primary bone lymphoma can arise in the sacrum, albeit rarely. Histologic appearance of these tumors can be similar, as both are characterized by small, round blue cells. Ewing's sarcoma has a characteristic t(11;22) chromosomal translocation, and is rare in patients older than 30 years of age.¹¹⁹ In a series of nearly 800 Ewing's patients, Bacci et al. found that only 2% of cases involved the sacrum. Importantly, they noted that sacral Ewing's tumors had a poorer prognosis compared to tumors elsewhere in the spine and in the extremities.¹²⁰ Treatment typically consists of neoadjuvant chemotherapy followed by surgery; adjuvant radiation may also be used.

Primary lymphoma of bone typically occurs in patients older than 40 years of age, with 10% of cases arising in the spine; a small subset of these is sacral tumors. Typically these tumors are very sensitive to chemotherapy and radiation, and surgery is rarely needed.^{119,121,122}



Figs. 118.2A to D: Images from a 19-year-old female with a sacral aneurysmal bone cyst, who presented with two years of sacral pain, exacerbated by 2 months of posterior leg radicular pain and bowel obstipation. (A) A large lytic area was eccentrically located within the sacrum on the pelvic radiograph. (B) Axial T2 MRI. (C) CT demonstrated a large mass eroding the sacrum and extending into the pre-sacral space. The tumor was removed via an all-posterior approach, sacrificing the S5 nerve roots only. Most of the tumor was removed en bloc; there was a positive margin superiorly that was curetted and treated with adjuvant alcohol and phenol. (D) At 5-year follow-up, the patient remained disease-free. Gross pathology sectioning of the tumor demonstrated a bony cystic lesion, characteristic of ABC.

Use of Stereotactic Radiation

Advances in radiation delivery technology have expanded options for using RT against sacral tumors. Conventional external beam radiation generally lacks the targeting accuracy necessary to avoid significant damage to the sacro-pelvic neurovascular structures while regularly delivering therapeutic doses.^{117,118} However, the advent of stereotactic body radiation therapy (SBRT) has made radiation a much more useful treatment for spinal tumors. Because the radiation dose can be very specifically conformed during delivery, malignant lesions can now often be treated with a single

dose of radiation while protecting the spinal cord from damage.^{118,123} Candidates for SBRT typically have either new focal or oligometastatic lesions and stable systemic disease, or have recurrent lesions after RT and are poor surgical candidates. Patients with neurologic compromise or less than 5 mm distance between the tumor and spinal cord are not candidates for SBRT.¹²⁴ Benign sacral tumors such as GCTs and ABCs can also be radiated using SBRT if surgical resection would cause unacceptable morbidity. However, although SBRT minimizes radiation damage to surrounding tissues, the risk of radiation-induced sarcoma still exists. Because of the increasing evidence for other

treatments such as serial embolization and denosumab, SBRT for benign tumors should still be used as a relative last resort, particularly in younger patients.^{114,117}

RESECTION TECHNIQUES

Appropriate perioperative planning is critical for achieving a successful surgical procedure. Massive blood loss can occur during sacrectomies, with bleeding up to 80 L reported for two-stage total sacrectomies.^{9,125} Intralesional resections of sacral tumors can also result in operative blood loss in excess of 30 L, even after preoperative embolization.² The anesthesia team should be prepared to administer large volumes of transfused blood throughout the case, replenishing platelets and coagulation factors in accordance with a massive transfusion protocol.

Neuromonitoring may or may not be useful, depending on the level and objective of the planned surgery. If en bloc resection is planned, then whichever roots are involved with the tumor must be sacrificed. However, if a nerve-sparing approach is performed, such as a debulking of a metastatic tumor, then neuromonitoring of the anal sphincter may be informative, particularly if the tumor is at or above S2. If posterior instrumentation is being placed, then triggered EMG should be performed for each pedicle screw to insure safe placement. Monitoring somatosensory evoked potentials (SSEPs) of the upper and lower extremities provides useful information if the case is lengthy, alerting the surgical team to compressive neuropathies from patient positioning.

Anterior sacral approaches are done to directly ligate vessels feeding the tumor, and to separate presacral visceral structures from the tumor to identify the appropriate anterior level for the sacral osteotomy. A longitudinal midline abdominal incision is used, and either a transperitoneal or retroperitoneal approach is made to the anterior sacrum. The iliac vessels, ureters, and femoral and obturator nerves should be identified and freed. If a rectus abdominus myocutaneous flap is to be used in reconstruction, the flap can be prepared during the anterior approach to allow pull-through once the posterior resection is completed. A silastic sheet can be placed between the sacrum and rectum to maintain demarcation and assist with the posterior resection.^{9,126,127}

The posterior approach is made using an inverted-Y incision ("Mercedes logo" incision) centered over the sacrum, with the arms of the Y extending around the anus and over the buttocks. Prior to skin sterilization and draping, the rectum should be packed with gauze to allow easy

palpation of the rectum during resection, minimizing the risk of inadvertent perforation. The resection may require excision of a substantial portion of the gluteus maximus muscle as a wide margin, if there is posterior tumor extension. The distal extent of the tumor is identified, and the coccygeal attachments of the sacral ligaments and pelvic floor muscles are released with electrocautery. The surgeon can then bluntly dissect along the anterior distal sacrum, packing surgical sponges into the presacral space to separate the rectum from the tumor. Once the lateral border of the tumor is identified, the piriformis muscles are resected as they emerge laterally from the anterior surface of the sacrum. Care must be taken to identify and protect the sciatic nerves at this portion of the resection. The proximal extent of the tumor is then delineated and the appropriate level selected to begin the posterior-to-anterior sacral osteotomy. The sacral canal is entered by performing a laminectomy. Once the dura is identified, the sacral nerve roots can then be unroofed at the level of the osteotomy using Kerrison rongeurs. Just distal to the pair of sacral roots that are not involved in the tumor and will be preserved, the dural sac is tied off with silk sutures and ligated. Osteotomes can then be used to create a cut through the sacrum while protecting the preserved nerve roots with Penfield neural retractors.^{9,126,127}

Cho et al. achieved en bloc resection of a sacral alar chondrosarcoma using computer-aided navigation. They were able to preserve all sacral nerve roots while performing the surgery through a posterior-only approach.¹²⁸ Sternheim et al. demonstrated that use of computer navigation can produce highly accurate sacropelvic osteotomies in a simulated sacral tumor model. Navigated osteotomies were significantly more accurate than non-navigated cuts ($P < 0.01$).¹²⁹ Bederman et al. recently utilized a surgical robotics system to guide osteotomies for a sacroiliac osteosarcoma resection.¹³⁰

RECONSTRUCTION TECHNIQUES

Stable reconstruction after resection of large tumors involving the sacrum is critical and often difficult. Biomechanically, the sacrum functions as the keystone of the pelvic ring, transferring axial loads from the entire spine to the hip joints via the sacroiliac joints. Substantial mechanical loading occurs at the lumbosacral and sacroiliac articulations with ambulation, standing and sitting.¹³¹ Typically if S1 is left intact, corresponding to 50% of the sacroiliac articulation, then the sacrum and pelvis are stable and do not require reconstruction.^{2,9,132,133}

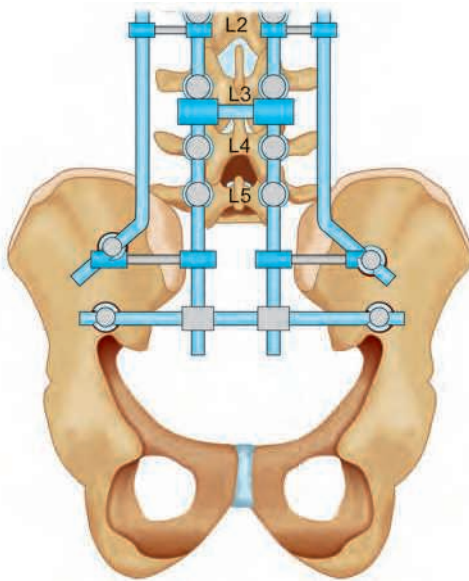


Fig. 118.3: Schematic representation of a 4-rod, 4-iliac screw technique for reconstruction after total sacrectomy.
Source: Adapted from Reference 137.

If reconstruction is needed, numerous techniques have been described. Broadly, constructs should restore posterior pelvic ring integrity, lumbopelvic continuity and anterior column support.¹³⁴ In addition, constructs should be rigid enough to enable early patient mobilization.¹³⁵ A modified Galveston rod technique was an early method of lumbopelvic reconstruction, but the iliac rods were noted to frequently loosen and break.^{9,136} In attempts to improve stability, Melcher and Harms employed dual contoured cylindrical cages to provide support between the inferior-most lumbar endplate and the posterior ilium, backed up with posterior segmental instrumentation.¹³¹ Kelly et al. and Mindea et al. performed biomechanical testing on several instrumentation configurations after cadaveric total sacrectomy, concluding that a 4-rod, 4-iliac screw construct had the most rigidity (Fig. 118.3).^{136,137} Two other studies tested a modification of this 4-rod technique by adding fibular strut grafts to form a triangle between the inferior endplate of the L5 body to the pelvis. The fibular grafts increased stiffness and achieved better load dispersion than the 4-rod construct alone by supporting the anterior column, although it should be noted that this technique requires a very extensive surgical exposure.¹³⁸⁻¹⁴⁰ Gillis et al. utilized a 2-rod construct with a unilateral vascularized fibular graft for reconstruction after a hemisacrectomy (Fig. 118.4).¹⁴¹

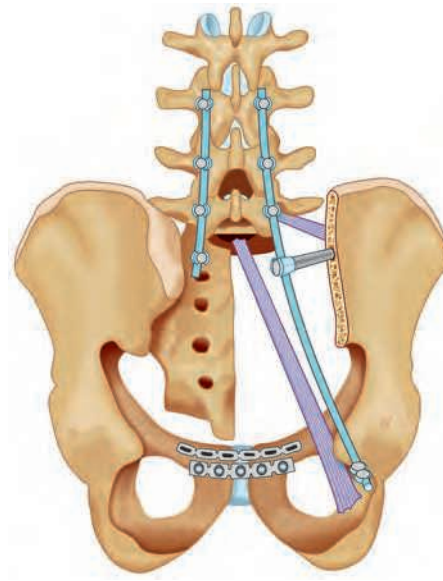


Fig. 118.4: Technique for reconstruction after hemisacrectomy. A vascularized fibula graft is placed between the L5 inferior endplate and the ischium, held in place by compression of the rod construct. A shorter fibular allograft is placed as a strut between the posterolateral L5 body and the posterior ilium.
Source: Adapted from Reference 141.

Based on current evidence, four iliac screws should be used for total sacrectomy reconstructions. Typically, 8.5 mm diameter screws can be placed between the inner and outer tables of the ilium. Screw length should be maximized (minimum length 80 mm) to obtain purchase in the supra-acetabular bone, placing the screw tips well anterior to the lumbosacral pivot point. Doing so improves biomechanical stability, thereby reducing the risk of screw pull-out and instrumentation failure.¹⁴²

COMPLICATIONS

The intraoperative and perioperative complication rate of sacral resections is high. Wound complications occur in 25–50% of cases, often requiring myocutaneous flap coverage. Previous radiation treatment to the surgical field is associated with increased risk of wound breakdown.^{24,42,46,132} Several studies have found that use of a rectus abdominus myocutaneous flap at the time of resection significantly reduced wound complications ($P = 0.01$).^{42,43} Sacral alar stress fractures can also develop, particularly after RT.⁴³ Cerebrospinal fluid leaks, vascular injuries, bowel perforations, and implant failures are other risks of sacral resections.^{9,82,86}

CONCLUSION

In conclusion, sacral tumors present diagnostic and therapeutic challenges for spine surgeons. An experienced multidisciplinary team is critical to achieving the best outcomes for these patients. Resections can involve substantial blood loss and carry a high risk of wound complications. Reconstruction techniques have improved as posterior segmental instrumentation options have expanded, and most patients can return to ambulation even after total sacrectomies. Sacrifice of sacral nerves carries significant implications for patient quality of life, requiring thorough preoperative patient discussion. Nonoperative treatments have expanded over the past decade, and include medical therapy with denosumab and bisphosphonates, serial embolization, sacroplasty and percutaneous ablations. In addition, stereotactic body radiation treatments have greatly improved the accuracy of RT for sacral malignancies. More high-level evidence is needed to clarify treatment algorithms and best practices for sacral tumors.

KEY POINTS

- Sacral tumors are challenging neoplasms, requiring experienced multidisciplinary teams for effective treatment
- Surgical resection with wide margins remains the mainstay treatment for most primary sacral malignant and aggressive benign tumors
- Prior to surgical treatment of sacral tumors, patients should be thoroughly counseled as to the implications of morbidity after sacral nerve root sacrifice, including bowel and bladder incontinence as well as sexual dysfunction
- Nonsurgical treatment options for sacral tumors are expanding: medical therapy with denosumab or bisphosphonates, serial embolization, sacroplasty and percutaneous ablations can all be employed against a number of sacral neoplasms
- Stereotactic body RT has made radiation a much more viable treatment option for malignant sacral tumors.

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- Recent biomechanical analysis of various sacrectomy reconstruction constructs proposed in the literature over the past two decades. Provides a good summary of multiple construct types that are tested with a robust simulation model.

Metastatic Tumors of the Spine

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Snapshot

» Clinical Findings

INTRODUCTION

Bone is a frequent site of occurrence of metastases from carcinoma, second only to lung and liver.¹ The bony elements of the spine, mostly the vertebral body, are the most frequently affected region. The vertebral bodies are reached largely via the bloodstream and neoplastic substitution of the bone tissue causes progressive structural destruction, leading to loss of stability and resultant compression of the nervous structures within the spinal canal.

There is evidence that blood from many anatomic sites drains directly into the axial skeleton. In postmortem studies, Batson² demonstrated that venous blood from the breast and the pelvis flowed not only to the vena cava but also into a venous plexus extending from the pelvis to epidural and perivertebral veins. The drainage of blood via the vertebral venous plexus may explain, at least in part, the tendency of breast, prostate, kidney, and lung to produce metastases in the axial skeleton. Currently, this is not accepted as the complete explanation, as molecular and cellular biology of the tumor cell and the tissue to which they metastasize influences the pattern of metastatic spread. Tumor dissemination is a multistep process involving specific tumor and host-tissue interactions via specific molecular determinants. In recent years, many basic and translational studies focused on angiogenesis, which enables growth of the primary tumor, access of tumor cells to the systemic circulation, and growth of micrometastatic deposits.

It is estimated that 20–30% of patients affected by carcinomas will develop symptomatic spinal metastases^{3,4} and about 40% will have evidence of bone metastases at autopsy.⁵ Back pain in a patient with a previous history of cancer should first arise the suspicion of metastatic disease rather than degenerative disease, which is the cause in the majority of the population. As stated by Perrin,⁶ “it is axiomatic that a cancer patient with new-onset back or neck pain harbors spine metastasis until proven otherwise.”

Conversely, primary bone tumors of the spine are extremely rare, with occurrence ranging from 20 to 50 times less frequently than metastasis. The knowledge of clinical and imaging patterns, as well as the epidemiology, incidence, and characteristics of different primary bone tumors, is crucial to suspect these diagnoses to perform a biopsy. Infectious bone diseases are also to be considered among the differential diagnosis. The different clinical pattern and images of disc erosion usually suggest the diagnosis, which will be confirmed by histology and cultural exams.

The incidence of vertebral metastases is increasing in time, paralleling the increasing life expectancies of cancer patient secondary to the improvement in medical, surgical, and radiotherapeutic treatments.⁷ Quality of life becomes the major concern not only for patients whose primary tumor is controlled but also for patients with widespread disease, where the pain cannot be relieved by drugs and/or ambulation is restricted by spinal insufficiency.

The choice of the most suitable treatment is of crucial importance to avoid that the patient be severely disabled by uncontrolled or recurrent spinal metastases, which is particularly difficult to accept if the primary tumor is controlled.

In order to improve the patient's quality of life, neurological function must be protected or restored, the spinal column must be stabilized and the pain must be relieved.

The reduction in the tumor mass, or debulking, or complete excision of the lesion is important⁸ for the local control of the disease. Bone metastases are evidence of a systemic disease, and therefore require multidisciplinary treatment, integrating radiotherapy,⁹ chemotherapy, and surgery.^{10,11} The best treatment protocol to adopt is still a matter of discussion.¹ The commonly accepted indications for surgery are symptomatic cord compression, spinal instability, intractable pain, and failures of precedent treatments. What is still debatable is the choice of the optimal surgical technique. New procedures and progresses in technology make the decision very difficult.

A wide range of surgical and parasurgical techniques are available, from the most aggressive (enbloc vertebrectomy, gross total excision) to minimally invasive techniques (vertebroplasty, percutaneous fixation, thoracoscopic excision). The interest in minimally invasive procedures is increasing by combining these techniques with attempts at tumor reduction via radiofrequency ablation (RFA)¹² or electrochemotherapy. What is unquestionable is the need for a multidisciplinary decision-making process to tailor the treatment for each patient, carefully considering cost-benefit ratio of all the possible treatment options available today. Staging systems and algorithms are proposed for the reproducibility of these decisions.

CLINICAL FINDINGS

Pain is the first and most serious symptom that patients with spinal tumors complain of. Pain is extremely frequent, nonspecific, and easily undervalued. Many times the pain is unrelated to activities and increases during the night. Vertebral collapse or impending fracture may change the character of the pain.

Many factors influence the onset of pain: tumor infiltration into the vertebral body expands and breaks the cortex, stretching the periosteum, stimulating the pain receptors of the periosteum; tumor invasion of the surrounding soft tissues; tumor invasion of the spinal canal and compression of the spinal cord and/or the nerve roots; and bony

erosion by the tumor can weaken the vertebra and cause mechanical pain.

In this case of loss of structural support, the patient complains of pain with standing when thoracic and lumbar vertebrae are involved or compelled to support the neck in the case of cervical location involvement. Pathological fracture results in an acute increase in pain and difficulty to stand in ways similar to that caused by a traumatic fracture. The structural alteration may lead to spinal instability and/or compression of the spinal cord. Neurological symptoms are not rare at the onset either as radicular pain and motor weakness due to root compression or as quad- or paraplegia due to cord or cauda equina compression secondary to canal encroachment.

Imaging and Diagnostic Studies

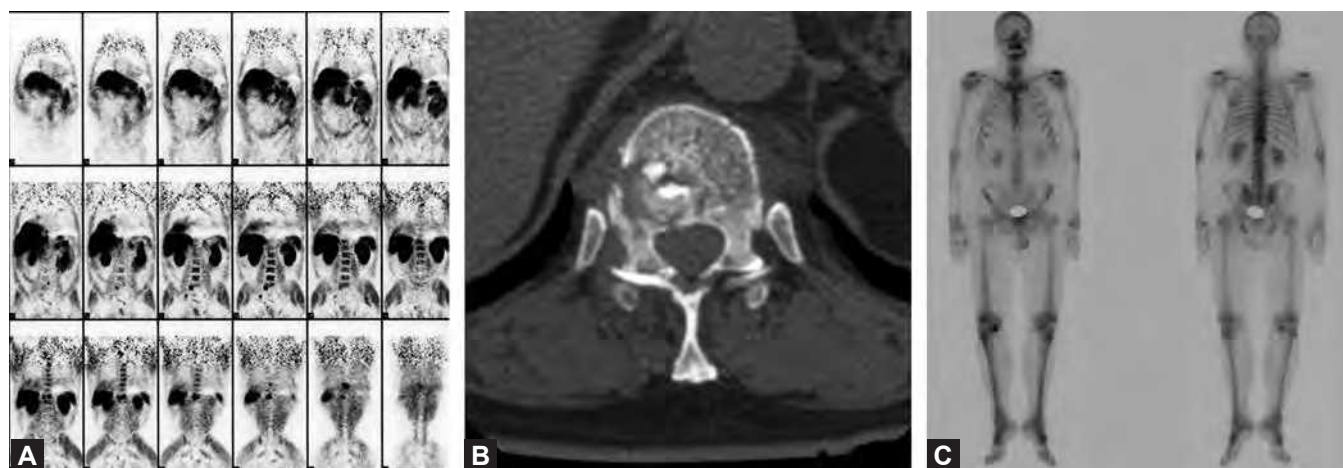
The majority of spinal metastases occur in the vertebral body, arising from the posterior wall and sometimes expanding into one of the pedicles. Not >5% are located exclusively in the posterior elements; in these cases, biopsy is mandatory to exclude other more probable conditions. A lytic pattern (Figs. 119.1A and B, 119.6A, and 119.7A and B) is more frequent than blastic (Figs. 119.2B and 119.3B). Rarely both aspects can be encountered in the same patient (Figs. 119.3A and B). A mixed aspect combining radiolucent and radiopaque lesions is most commonly found (Fig. 119.3C).

Osteolysis resulting in bone destruction does not appear to be simply a mechanism of tumor-replacing bone, but rather activation of osteoclasts causing dysregulated remodeling of bone.¹³ Osteoblastic metastases, mostly as a result of prostate cancer (Fig. 119.2B), though sometimes observed in breast metastases (Figs. 119.3A and B), arise via the stimulation of osteoblasts by several factors, including transforming growth factor beta, fibroblast growth factors, prostate-specific antigen (PSA), and bone morphogenetic protein. Mixed aspects are combinations of neoplastic-induced erosive actions and bone-forming reaction or collapse of trabeculae. Sclerotic reaction around the lesion or ossification inside the tumor mass can be a sign of good response to therapy (Fig. 119.7E).

The presumed cascade of events of lytic metastases is correlated to the resolution and the specificity of different imaging techniques. Magnetic resonance imaging (MRI) can demonstrate the bone marrow invasion, the first step of metastatic seeding inside the cancellous bone of a vertebral body, even before any destructive effect on bone.



Figs. 119.1A and B: A 69-year-old male. T12 lytic lesion. Metastasis from lung cancer. Pain related to standing position and during bending. No body collapse and unilateral involvement of posterior elements. SINS 9



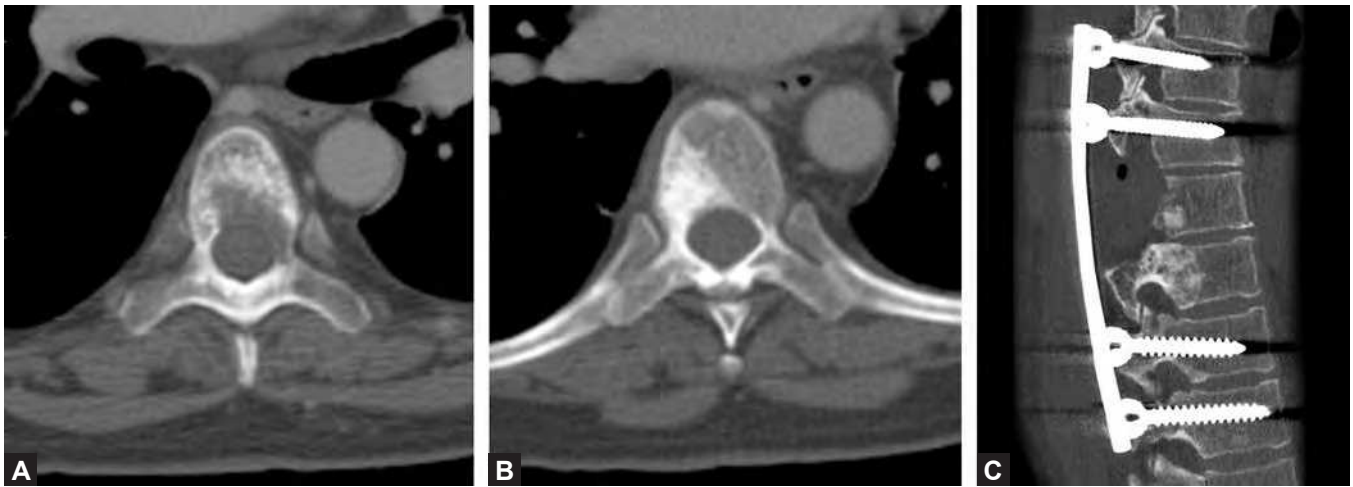
Figs. 119.2A to C: A 77-year-old male. Prostate carcinoma. Nocturnal back pain. (A) PET scan positive in T12. (B) Sclerotic metastasis SINS score 4. (C) Bone Scintigraphy shows uptake of the contrast at T12.

Uptake of the tracer in bone scintigraphy becomes evident as soon as osteoblast activity initiates (Fig. 119.2C), while computed tomography (CT) scans begin showing changes when trabecular destruction appears. Finally, plain films show diagnostic images when the tumor provokes cortical erosion, destroys >30% of cancellous bone or causes a significant sclerotic reactive bone formation (Fig. 119.6F). Because of anatomical superimposition of the sternum and ribs, lesions occurring from C6 to T4 are particularly difficult to visualize on plain films; CT scan and MRI become mandatory to detect a lesion suspected on bone scintigraphy. The well-known “winking owl” (Fig. 119.5) finding signifies the disappearance of the pedicle in the coronal

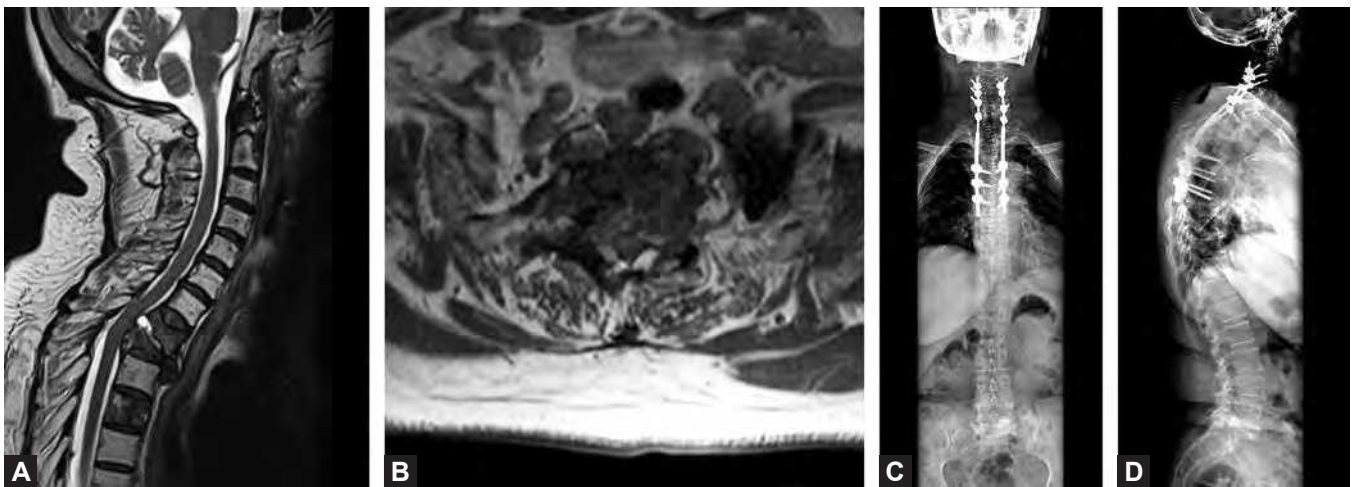
view provoked by a lytic metastasis eccentrically destroying the vertebral body and the pedicle is a late manifestation of the disease. With improved diagnostic ability and improved awareness, the diagnosis of metastatic spinal lesions should be made quite earlier.

The role of conventional plain radiograph is limited to follow-up of hardware (Fig. 119.3C) or to the analysis of sagittal balance when performed in standing position (Fig. 119.4D).

Computed tomography scans allow detection of both lytic and blastic lesions: blastic lesions easily identified as increased calcification and lytic lesions visible as fat is replaced by tumor in the bone marrow. Erosion of the



Figs. 119.3A to C: A 64-year-old female. Multiple metastases from breast cancer (A and B). Metastatic cord compression at T7-T8. Sclerotic lesion in T8 without fracture, with unilateral involvement of posterior elements; SINS 3. Lytic lesion in T7 in absence of pathological fracture with unilateral involvement of posterior elements. Normal alignment; SINS 5. (C) Due to spinal cord compression the patient underwent to a surgical decompression and stabilization.



Figs. 119.4A to D: A 63-year-old female T1-T2-T3-T4 metastases from breast cancer. Cervical-dorsal pain under loading, needs to support the head with the hands. (A) MRI T2 weighted sagittal image of the cervicothoracic spine showing collapse, subluxation and translation. Collapse of T2 vertebral body. (B) Axial image of T2 showing bilateral involvement of the posterolateral complexes. Other metastatic localization at T4; SINS 18. (C and D) Postoperative X-ray; C3 to T8 decompression and stabilization.

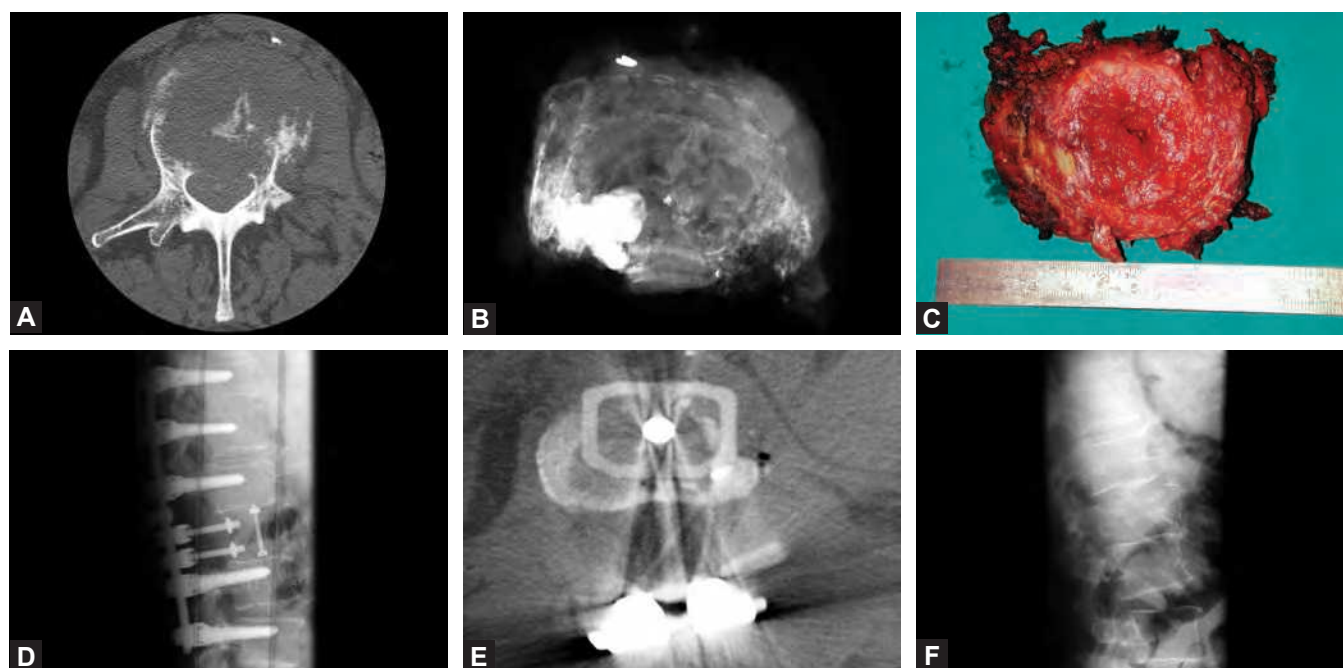
cortex and soft tissue encroachment can also be seen, enhanced with the administration of intravenous contrast media.

Magnetic resonance imaging allows early detection of changes in bone marrow consistency and is considered the best procedure in soft tissue investigation. On T1-weighted images, normal bone marrow is hypointense in children, and then progresses with age from isointense to hyperintense in elderly people. The signal for metastatic

deposit is of low intensity, very low for osteoblastic lesions (Fig. 119.4A). On T2-weighted images, the signal is variable, mostly hyperintense. The stir T2 sequence is more sensitive than T1- and T2-weighted images for detecting metastases, but conversely is less sensitive for observing extravertebral involvement (Figs. 119.4B to D).¹⁴ These sequences are also hyperintense in osteoporotic fractures (Fig. 119.8); however, cancellous bone pattern disruption, cortical erosion, and soft tissue masses will be helpful to differentiate metastatic lesions.



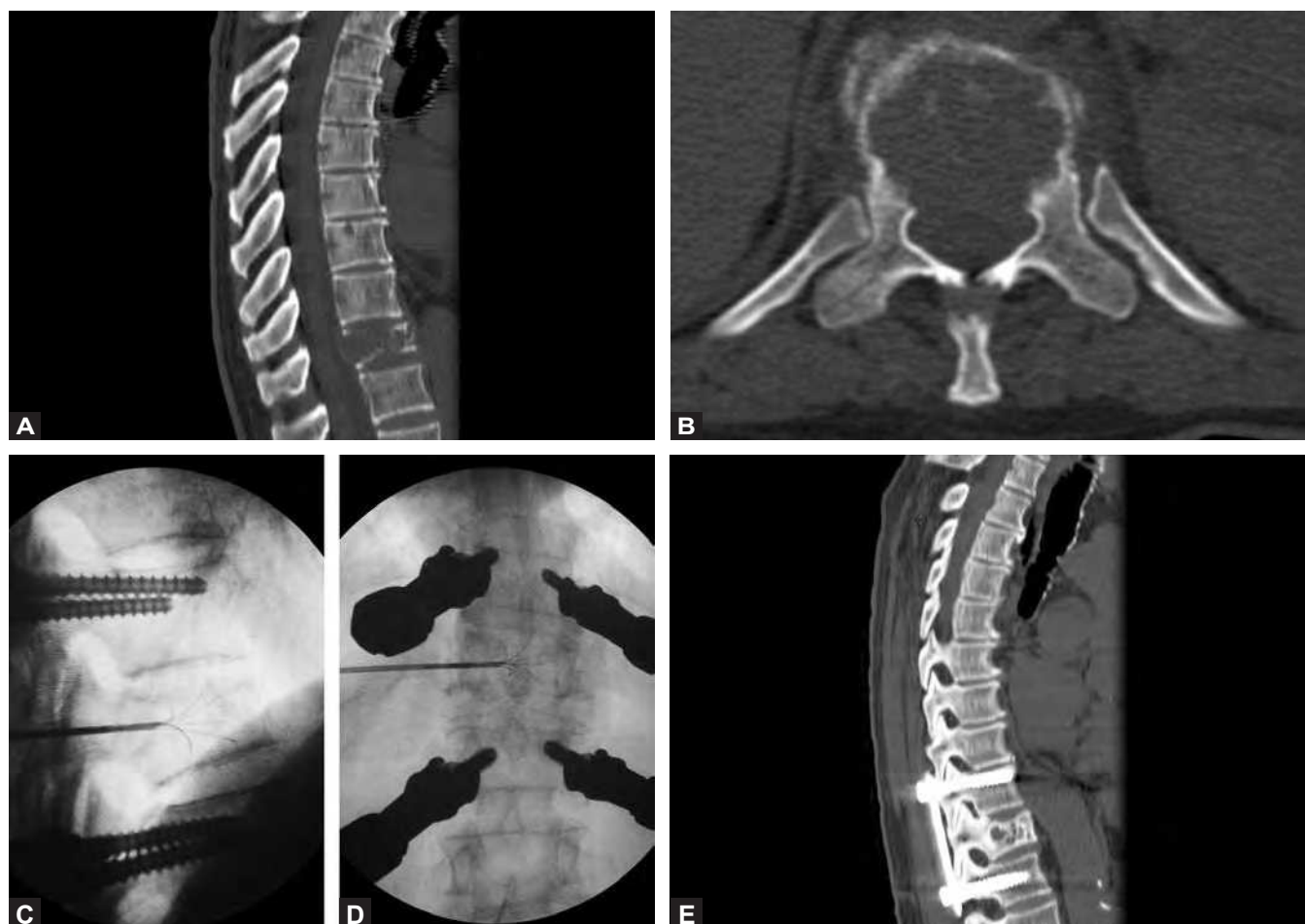
Fig. 119.5: Winking owl sign.



Figs. 119.6A to F: A 58-year-old male. Solitary metastases from hypernefroma. Pathologic fracture of L2 (A and F) with osteolysis involving >50% of the vertebral; non involvement of posterior elements. SINS score: 12. (B and C) En bloc resection with wide margins, upper view. (D) Postoperative X-ray showing anterior reconstruction with carbon fiber stackable cage and posterior stabilization with screws and rods. (E) Axial CT scan image showing the carbon fiber cage, in the right position, filled with autologous bone graft.

Bone scintigraphy with technetium-99 is a screening technique with high sensitivity but low specificity in detecting lesions (Fig. 119.2C). It evidentiates the bone-forming reaction but does not demonstrate the presence of tumor tissue itself unless pathologic bone is formed. It reflects the rate of bone turnover, so “hot spots” can be seen

in many benign lesions, like osteoid osteoma, trauma, and infections. It is a relatively low-resolution technique and may miss small lesions or lesions that are purely lytic. The advantages are that it is a whole body screening method, low cost, and low irradiation of the patient. It is rarely used alone; it needs to be considered in association with other



Figs. 119.7A to E: A 76-year-old male. Hepatocellular carcinoma. Metastases in T11 with collapse of the endplates (A and B). Severe pain, preventing to standing, <50% body collapse, no involvement of the posterolateral complexes, normal alignment. SINS score: 12. (C and D) Radiofrequency ablation and minimally invasive fixation. (E) 18 months follow-up, no signs of local recurrence, bone reconstruction.



Figs. 119.8A and B: A 77-year-old female. 3 weeks before sudden back pain, not related to trauma, after mild effort. (A and B) T2-weighted and STIR sequence shows hyperintense image in L4 without pattern of disruption neither soft tissue masses. Suggestive for osteoporotic fracture.

imaging technique, such as CT or MRI to better characterize any abnormalities.

Positron emission tomography (PET) previously considered as a research tool is now rapidly increasing in clinical applications specifically in detecting and staging metastatic tumors (Fig. 119.2A). Unlike conventional anatomic imaging methods, PET is able to detect functional and metabolic changes and is intrinsically more sensitive. The most commonly used tracer in clinical PET is 18 F-fluoro-deoxyglucose (18FDG); FDG-PET has higher costs but a far better spatial resolution than ^{99m}Tc bone scan. Its major advantage is imaging tumor specifically and not bone formation. It is a whole body method for detecting bone and soft tissue tumors based on the increased glucose avidity of tumors with increased metabolism. The disadvantage is that not all bone tumors are hypermetabolic and therefore not constantly detectable. Kidney, prostate, and ovarian carcinoma as well as breast carcinoma at early stages are poorly glucose avid; mucin (gastrointestinal) tumors are doubtful; while lung cancer, lymphoma, and advanced breast tumors are very avid with the highest possibility of detection. For these and other conditions under evaluation, FDG-PET seems to be a promising tool for staging and for evaluating the response to therapy.

For both diagnostic and therapeutic assessment of infective spondylodiscitis, FDG PET/CT has already been proven to be sensitive and accurate.¹⁵ Standardized uptake value (SUV) at diagnosis of spondylodiscitis was $8.6 (\pm 3.7)$ in 34 patients.¹⁶ The quantitative analysis of SUV is therefore helpful to differentiate from bone tumors that have a max SUV of $4.3 (\pm 3.1)$.¹⁷

As reported previously, max SUV is variable in metastases, mostly inferior to the value detected in infectious disease. In cases of non-small cell lung cancers, the SUV are higher and the prognostic value of preoperative 18F-FDG PET has been recently enhanced.¹⁸

Tumor Markers

Several markers are elevated in metastatic breast cancer and can confirm the radiological suspect. These include serum carcinoembryonic antigen, the mucin markers CA 15-3 and CA 549, and tissue plasminogen activator. An elevated level of CA15-3 is highly suggestive of metastatic disease, but 30–40% of patients with bone metastasis from breast carcinoma have normal CA 15-3 levels.¹⁹ Prostate-specific antigen has proven useful in the early diagnosis, staging, and follow-up of patients with prostate cancer;

however, poorly differentiated tumors produce lower levels of PSA.

Diagnosis

Detecting a lytic or blastic symptomatic radiographic finding is not pathognomonic for metastatic disease even in a patient with known cancer. Moreover, patients with two or more cancers are not rare, and imaging is not helpful to suggest which is the symptomatic metastasis. The differential diagnosis of spinal lesions should also include infectious diseases, primary malignant, and benign tumors. For example, hemangiomas are encountered frequently. Osteoporotic collapse or compression fractures (Figs. 119.8A and B) are very frequent in the elderly and in metabolic diseases, but can occur during the clinical course of a tumor patient, particularly if submitted to chemotherapy and if physical activity is reduced.

A spine metastasis can be the first clinical occurrence and can remain for a long time the only manifestation of the distant spread of an unknown disease; familiarity with the radiographic pattern of different primary bone tumors is helpful to guide diagnosis. As stated above, lesions arising from the posterior arch should be suspected for primary tumor:

- *Chondrosarcoma*: Lytic, with round ossifications, sometimes evident is the original exostosis.
- *Aneurysmal bone cyst*: Bubbly with typical double density content on MRI or contrast-enhanced CT scan; a circumferential sclerotic border with erosion of the normal bone.
- *Osteblastoma*: Mixed, mostly blastic, sometimes with fuzzy borders.
- *Hemangioma*: Corduroy image in coronal and sagittal, corresponding to polka dot images on transverse sections is suggestive for hemangioma. Hemangiomas are the most frequent benign bone condition in the spine, occasionally found more lytic and locally aggressive.
- *Hemangioendothelioma*: Characterized by lytic change of the vertebral profile, mostly enlarged with possible peripheral ossified border, and internal trabeculae of different thickness. Hemangioendothelioma is an infrequent lytic tumor of vascular origin.
- *Chordoma*: A lytic lesion centrally located in the vertebral body that arises from the posterior wall and infiltrates the cancellous bone, invading the epidural space and expands in the paravertebral regions, possibly creating huge soft tissue myxoid masses.

- Myeloma is fully lytic and therefore almost always negative on ^{99m}Tc scan; however, a pathologic fracture can occur early in the disease, giving a positive result on a ^{99m}Tc scan.
- Much rarer are osteosarcoma, angiosarcoma, and Ewing's sarcoma.
- *Infection*: A lytic lesion involving a disc and the contiguous vertebral bodies is strongly suggestive for infection. The suspect of spondylitis or spondylodiscitis is sometimes erroneously ignored. The incidence of these conditions in the normal population is not negligible; moreover, as cancer patients submitted or not to chemotherapy are presumably immunodepressed. This possibility should particularly be considered in the differential diagnosis of a metastatic disease.

Biopsy to provide material for histological study is the best and fastest way to a diagnosis, and frequently in case of metastases is also suggestive of the primary lesion: mucoid appearance for gastrointestinal tumors, clear cells for renal cancer, and small cells for lung cancer. However, biopsy can be avoided in cases of diffuse metastases in a patient with well-known carcinoma, or the incidence of metastatic disease at short distance after breast carcinoma simultaneous with increasing levels of specific biochemical markers. Additionally, the oncologist can request a biopsy if treatment has started without histological confirmation or if the lesion increases in size after treatment has begun.

A safe technique to perform a bone biopsy is with a trocar under CT guidance. This allows minimal soft tissue contamination and specimen sampling from the representative and viable portion of the tumor. Bone biopsy should be performed with a trocar rather than fine needle aspiration, in order to provide the pathologist with a sufficient quantity of specimen, which is representative of the tissue architecture.

Surgical Options

Refinement of the protocols for treating tumor patients has led to a progressive improvement in the prognosis for many tumor histotypes in terms of mean survival time. As a consequence, the interest is growing on symptomatic spinal metastases, particularly in patients without other evidence of disease, if severely affecting their quality of life.^{1,20} Historically, the role of surgery for spinal metastases was largely confined to decompression of the compressed spinal cord and/or nerve roots.²¹⁻²⁴ Laminectomy alone has been proven to be mediocre in outcome and not more

beneficial than radiotherapy alone.^{24,25} Due to increasing patient expectations, in order to attempt complete local control and to provide the best functional results, more and more aggressive surgeries have been proposed for the treatment of spinal metastases.^{4,26,27} Conversely, to reduce the surgical morbidity especially in patients with poor general condition, less invasive surgical techniques have been developed, often combined with radiotherapy or other local tumor ablation techniques.

Commonly accepted indications for surgery include cord compression, pathologic fracture, intractable pain, and spinal instability caused by the lesion.²⁸ What is still a matter of discussion are the indications of the different techniques. The different surgical options are presented.

Laminectomy and Fixation

Laminectomy is targeted to decompress the spinal cord: It does not necessarily include tumor removal, but complete decompression is achieved by the removal of at least part of the tumor mass invading the canal. If the tumor invades the vertebral body, surgical removal of posterior elements reduces the stability. Fixation is therefore mandatory to prevent collapse and secondary further cord compression. Rades²⁹ found that patients with metastatic spinal cord compression had improved functional outcomes, particularly those patients with an unfavorable primary tumor, from decompressive surgery plus stabilization compared to laminectomy and radiotherapy. Bilsky³⁰ from a systematic review considering 19 articles out of >80,000 titles concluded that decompression and instrumentation are the treatment of choice of epidural cord compression from solid tumor metastases.

In 2005, Patchell³¹ published the only prospective, randomized, multi-institutional trial comparing external beam radiation (30 Gy in 10 fractions) to decompressive surgery and instrumentation followed by external beam radiation therapy in 101 symptomatic patients with spinal cord compression. The primary tumor histology was lung carcinoma in 26 patients with 13 in each arm. Patients undergoing surgery and radiation therapy had statistically significant improvement compared to radiation alone in terms of preservation of neurologic function and pain relief. Notably, 57% of patients in the radiation arm maintained ambulation, but the duration was only 13 days compared to ambulation until death (122 days) in the surgical arm. No patient in the radiation group recovered ambulation without surgery.

There is further evidence that this surgical technique performed before radiation therapy results in improved neurologic outcomes and fewer wound complications rather than performed after.³² The morbidity of this technique can be reduced by percutaneous implant of the pedicle screws (Figs. 119.7A to E) and by microscopic or endoscopic decompression.

Tumor Debulking

Tumor removal, not only to decompress the cord but also to substantially reduce the tumor mass, is performed for local control when no other treatment is effective or available. This surgical procedure can be performed by anterior approach³³ or by posterior approach³⁴ or by combination, according to tumor extension and the need for a complete 360° reconstruction, providing the patient with appropriate sagittal balance. The morbidity of this technique can be reduced by percutaneous implant of the pedicle screws combined by microscopic tumoral excision or by tumor ablation by radiofrequency (Figs. 119.7A to E) or electroporation.

Selective Arterial Embolization

Selective arterial embolization (SEA) is an angiographic procedure performed to embolize the artery feeding a tumor. Its role as a therapeutic agent is questionable in metastases, though it plays a major role in the treatment of aneurysmal bone cyst and similar conditions.³⁵ The purpose of SEA in the treatment of metastases is to ischemize the tumor and decrease blood flow to the mass before intralesional excision. Only a few publications have succeeded to provide evidence supporting its use,³⁶ but expert opinions support a correctly performed SAE to significantly reduce the intraoperative blood loss, making surgery safer, less morbid and more effective, as the surgeon is able to remove much more volume of tumor than under profuse bleeding.³⁷⁻³⁹

The limit of this procedure in the spine is represented by the possible anastomosis of the tumor vascularization with the spinal cord arterial supply. The various interventions designed to embolize the tumor feeding arteries, such as particles, glue or spirals, could embolize the arteries supplying the cord, provoking an irreversible paralysis. The angiographer will necessarily perform a careful study of the vascular supply of the cord in order to detect possible anastomosis with the tumor vascularization to avoid this complication.

En Bloc Vertebrectomy

En bloc tumor removal is the treatment of choice of primary low-grade malignant tumors and must be considered exceptional for metastases.^{40,41} It is a technically demanding procedure with a high risk of complications.⁴² Once the criteria of feasibility are satisfied,⁴³ the indication in a metastatic lesion must be justified. A reasonable goal is to achieve the complete local control in a patient with a high chance of long-term survival.

Tumors with no or low sensitivity to other treatments, such as metastatic renal carcinoma and sarcomas, are the best indication, particularly if they are hypervascularized and intralesional surgery⁴⁴ carries a high risk of life-threatening bleeding during surgery. Bilsky in an exhaustive systematic review of the literature concluded that following en bloc resection, 40 cases of metastases from renal cell carcinoma experienced 7.5% local recurrence at a median follow-up of 16 months.³⁰

Vertebroplasty

Vertebroplasty is a minimally invasive technique, considered an interventional radiology technique, which consists of the injection of polymethylmethacrylate (PMMA) cement inside the vertebral body by percutaneous approach under radioscopic control or under CT guidance.²² Performed for the first time in 1984 by Deramond⁴⁵ in France for the treatment of an aggressive angioma of C2, it has undergone considerable development, extending its indications to the treatment of vertebral metastases. However, tumors inside the vertebrae are mostly solid, and if PMMA is injected in the vertebra without having first destroyed or removed the tumor, it may enter the vertebral canal or spread around the vertebra, potentially disseminating tumor cells.⁴⁶ Polymethylmethacrylate has no proven antitumoral effect, and if the tumor does not respond to adjuvant therapies, it will continue to grow. Cavitation by RFA followed by filling this void with PMMA seems a reasonable option. Finally, it should be noted that the morbidity associated with vertebroplasty, although low, is not negligible.⁴⁷

Vertebral augmentation by PMMA injection appears to be an interesting option in patients with diffuse disease to stabilize the spine and relieve pain, in situations where local tumor control is not a major concern. Absolute contraindications to vertebroplasty include the complete erosion of the posterior wall, retropulsion of fracture elements, and cord compression by tumoral mass expanding

in the canal. In these cases when PMMA is injected and pressurized, it can extravasate from the vertebral body and encroach upon the canal compressing the spinal cord; decompressive surgery should be best performed if the risk of spinal cord compression is high.

Staging and the Decision-Making Process

Once a metastatic lesion is diagnosed, even if solitary, it necessarily implies systemic disease. The decision-making process should start from a systematic evaluation of the patient and the disease. The medical oncologist holds a prominent role in estimating a reasonable life expectancy, as does the anesthesiologist, in assisting the determination of the patient to tolerate different surgical treatments. To select the most appropriate local treatment for each patient, the cost-benefit ratio of any surgical, chemotherapeutic, or radiotherapy treatment, in terms of morbidity versus established advantages, must be considered.^{1,26,48}

Speak the same language: In this multidisciplinary approach, the first requirement is to “speak the same language” in order to weigh every element on the same scale. Ideally, a scoring system or an algorithm could be helpful in order to make any decision reproducible and correlate treatment morbidity with expected outcome. A deterioration of neurological function can be recognized, the severity of pain can be mitigated, a pathologic fracture can be treated, but the identification and prevention of impending fracture remain a major issue. The concept of spinal instability is critical in this decision-making process. Instability, as the result of tumoral erosion, differs from the result of traumatic injuries, due to bony and ligamentous involvement, bone quality and the potential for healing, and therefore requires different criteria. The Spine Oncology Study Group, an international multidisciplinary group of spine oncology experts, has defined “spine instability” as (a) loss of spinal integrity as a result of a neoplastic process that is associated with movement-related pain, (b) symptomatic or progressive deformity, and/or (c) neural compromise under physiologic loads. They have proposed the Spine Instability Neoplastic Score based on patient symptoms and radiographic criteria to predict spine stability of neoplastic lesions.⁴⁹ This system includes spinal location of the tumor, type and presence of pain, bone lesion quality, spinal alignment, extent of vertebral body collapse, and posterolateral spinal element involvement.

Qualitative scores were assigned based on relative importance of particular factors gleaned from the literature and refined by expert consensus (Table 119.1).

Outcome evaluation: Outcome evaluation should be compared with the patient status at diagnosis. A largely accepted system to evaluate the quality of life is Karnofsky score,⁵⁰ a subjective measure of how well the patient is doing (see Table 119.2). It is useful to identify trends over time, as well as to see fluctuations in patient satisfaction throughout the disease process. The Karnofsky score is also sometimes used as a criterion for entrance into a clinical trial.

Scoring system: Several preoperative scoring systems have been proposed to classify patients affected by spine metastases and help guide the appropriate treatment. The various different classification schemes are justified by the frequency of the disease and need to standardize the selection of the appropriate treatment to show favorable outcomes and improve the quality of life.

Harrington classification, 1986: This was the first important attempt to stage patients with spine metastases.⁵¹ It divides patients who have spinal metastases into five categories, depending on the extent of neurological compromise or bone destruction:

- Class I: No significant neurological involvement
- Class II: Involvement of bone without collapse or instability
- Class III: Major neurological impairment (sensory or motor) without significant involvement of bone
- Class IV: Vertebral collapse with pain due to mechanical causes or instability but without significant neurological compromise
- Class V: Vertebral collapse or instability combined with major neurological impairment.

With this classification schema, the class guides the treatment. Class I or II patients generally obtain relief from pain by chemotherapy or other medical treatment, or, if unsuccessful, from local radiation therapy. Patients in Class III usually respond to treatment with radiotherapy alone. If the neurological compromise is acute, the radiotherapy should be augmented by systemic administration of steroids. Given that vertebral collapse is present in both class IV and V, these groups of patients are not likely to improve from irradiation alone, regardless how radiosensitive the underlying malignancy may be; surgical intervention is indicated.

Table 119.1: The SINS classification according to Fisher et al.⁴

	Score
Location	
Junctional (occiput C2, C7-T2, T11-L1, L5-S1)	3
Mobile spine (C3-C6, L2-L4)	2
Semirigid (T3-T10)	1
Rigid (S2-S5)	0
Pain*	
Yes	3
Occasional pain but not mechanical	1
Pain-free lesion	0
Bone lesion	
Lytic	2
Mixed (lytic/blastic)	1
Blastic	0
Radiographic spinal alignment	
Subluxation/translation present	4
De novo deformity (kyphosis/scoliosis)	2
Normal alignment	0
Vertebral body collapse	
> 50% collapse	3
< 50% collapse	2
Not collapse with > 50% body involved	1
None of the above	0
Posterolateral involvement of spinal elements[‡]	
Bilateral	3
Unilateral	1
None of the above	0

*Pain improvement with recumbency and/or pain with movement/loading of spine

‡Facet, pedicle, or costovertebral joint fracture or replacement with tumor.

Asdourian classification, 1990: The classification scheme proposed by Asdourian⁵² suggests surgical intervention in cases where increasing vertebral collapse (type IIB, type IIIA-B, type IV) corresponded to progressive instability and cord compression.

Bauer classification, 1995: Bauer proposed a scoring system suggesting “radical” surgery for patients with solitary metastasis without pathologic fracture, from primaries with relatively good prognosis without visceral localization (group C).⁵³

Sioutos classification, 1995: Sioutos⁵⁴ proposed that survival after surgical treatment of spine metastasis is affected by preoperative neurological status, primary tumor histotype and the number of involved vertebrae, but not by localized spread of the disease nor the age of the patient.

Katagiri classification, 2005: Katagiri⁵⁵ proposed a scoring system considering several prognostic factors: performance status, histotype, the presence or absence of visceral and brain metastases, multiple spine metastases, and previous courses of chemotherapy. A study published in the same year by Var der Linden⁵⁶ supported the Katagiri Classification by stating that surgery is indicated only in patients (group C) with favorable histotype, good performance status and without visceral metastases.

Rades classification, 2008: Rades⁵⁷ proposed a scoring system considering histotype, bone and visceral metastases, interval from primary tumor treatment and onset of spine metastasis, and neurological symptoms.

Tokuhashi classification, 1990: Tokuhashi⁵⁸ proposed a system that assesses the prognosis of metastatic spine tumors based on the six parameters given further:

Table 119.2: Karnofsky performance status scale KPS scale.

Able to carry on normal activity and to work; no special care needed	100	Normal no complaints; no evidence of disease
	90	Able to carry on normal activity; minor signs or symptoms of disease
	80	Normal activity with effort; some signs or symptoms of disease
Unable to work; able to live at home and care for most personal needs; varying amount of assistance needed.	70	Cares for self; unable to carry on normal activity or to do active work
	60	Requires occasional assistance, but is able to care for most of his personal needs
	50	Requires considerable assistance and frequent medical care.
Unable to care for self; requires equivalent of institutional or hospital care; disease may be progressing rapidly	40	Disabled; requires special care and assistance.
	30	Severely disabled; hospital admission is indicated although death not imminent
	20	Very sick; hospital admission necessary; active supportive treatment necessary
	10	Moribund; fatal processes progressing rapidly
	0	Dead

1. General condition
2. Number of extraspinal bone metastases
3. Number of metastases in the spine
4. Metastases to the major internal organs (lungs, liver, kidneys, and brain)
5. Primary site of the cancer
6. Severity of spinal cord symptoms.

In the scoring system, each parameter ranges from 0 to 2 points. The total score obtained for each patient can be correlated with and predict the prognosis. Excisional surgery is suggested for those cases who scored >9 points, while palliative surgery is indicated for those who scored <5 points. In 2005, Tokuhashi⁵⁹ revised his system, giving more importance to the primary site of cancer (0–5 instead of 0–2). This improved the predictivity of the prognosis from 62% to 81%. In patients with a total score of 12 or more (predicted survival period 1 year or more), excisional procedures are proposed. In patients with a total score 9–11, excisional procedures are indicated in a single lesion without metastases to the major internal organs. Palliative procedures are suggested in all other cases. Surgery was not indicated in patients with a predicted survival period of 6 months or less (score 0–8).

Tomita classification, 2001 (see Table 119.3): Tomita²⁷ proposed a scoring system for spinal metastases based on three prognostic factors:

1. Grade of malignancy (slow growth, 1 point; moderate growth, 2 points; rapid growth, 4 points)
2. Visceral metastases (no metastasis, 0 point; treatable, 2 points; untreatable, 4 points)
3. Bone metastases (solitary or isolated, 1 point; multiple, 2 points).

These three scores are added together to give a total score ranging from 2 to 10. A score of 2–3 points suggests treatment with wide or marginal excision for long-term local control; 4–5 points suggest intralesional excision for mid-term local control; 6–7 points propose palliative surgery for short-term palliation; and 8–10 points indicate nonoperative, supportive care.

These systems are limited because they guide treatment strategy based on arbitrary scores attributed to selected parameters. The benefit of these classifications is their attempt to standardize treatment and suggest the appropriate treatment. The score attribution is validated retrospectively on the outcomes studied. In certain schema, equal importance is therefore given to the various parameters, which may not be valid, as Tokuhashi's modification exemplifies. For example, the histotype of the primary tumor and the general condition of the patient have the same influence on the final score and therefore on the treatment selection.

A proposed algorithm for decision-making process: This algorithm^{48,60} was proposed as an alternative to these

Table 119.3: Classification of vertebral involvement by metastatic disease proposed by Tomita et al.²⁷

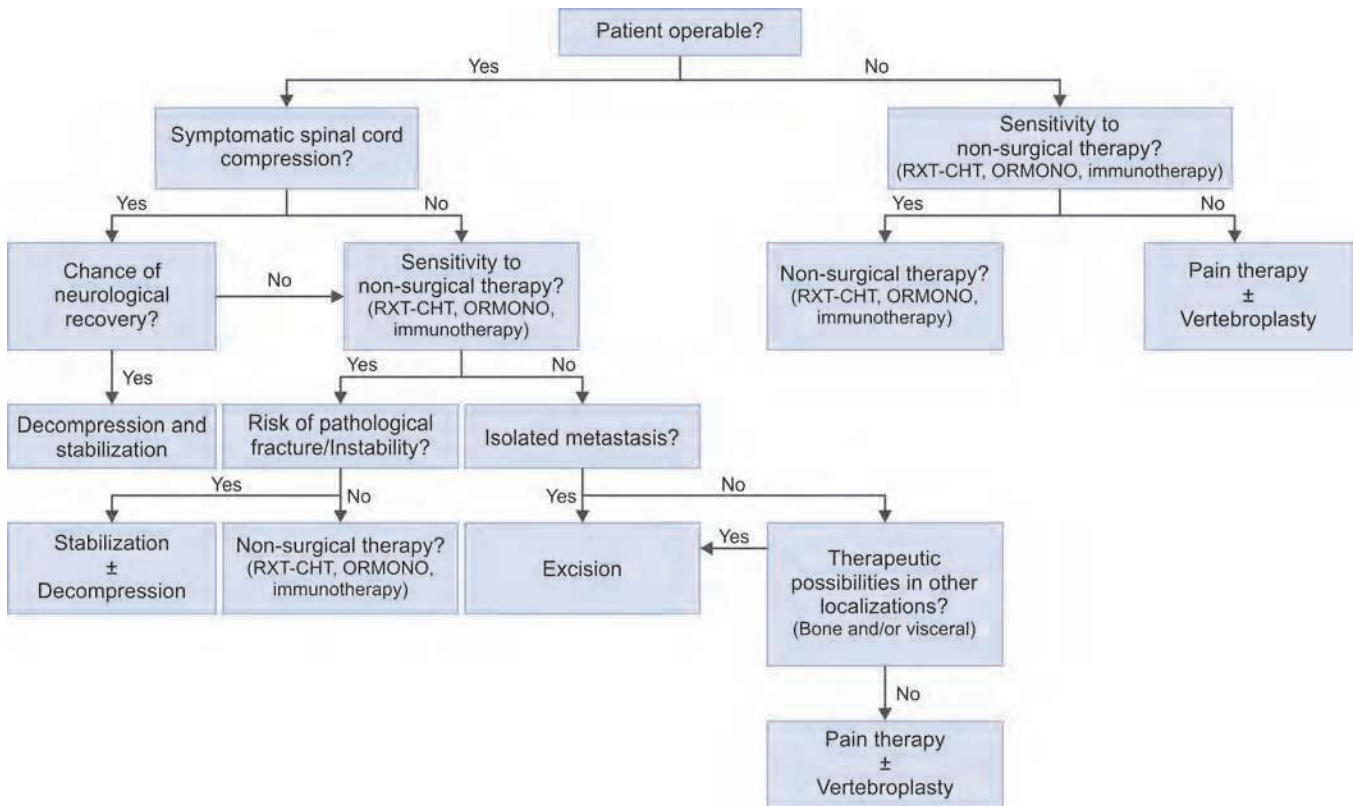
Intra-compartmental	Extra-compartmental	Multiple
Type 1 Vertebral body	Type 4 Epidural extension	Type 7
Type 2 Pedicle extension	Type 5 Paravertebral extension	
Type 3 Body-lamina extension	Type 6 2–3 vertebrae	

scoring systems, considering that the decision-making process for spine metastases is individualized. Each patient follows his or her “personal” sequential process that does not necessarily consider each of the parameters at every time point, as some may be irrelevant at certain time points in the decision-making process. For example, a patient in poor general conditions with a high ASA (American Society of Anesthesiologists) score⁶¹ is not a candidate for surgery irrespective of the histotype of the primary tumor or the number of secondary localizations. For these patients, the most important parameter will therefore be the sensitivity of the tumor histotype to adjuvant treatment. In the same way, a patient with acute and worsening spinal cord damage will undergo emergency palliative decompression and stabilization surgery even for patients with increased ASA scores. Surgical fixation and decompression can be performed by minimally invasive procedures or through standard open surgical techniques (see Fig. 119.3). This should be decided on a case-by-case basis according to the surgeon’s training and preferences. In some cases, such as hepatocellular carcinoma, evidence exists for tumor ablation by radiofrequency (see Figs. 119.7A to E).

The parameters considered in this algorithm are shown in Flowchart 119.1 and summarized as the following:

1. General condition and the ASA⁶¹ score
2. Sensitivity of the primary tumor to chemotherapy and radiotherapy
3. Neurological symptoms

4. Pathologic or impending fracture
 5. Systemic disease and possible treatment of visceral metastases.
- Once a spine metastasis is diagnosed, the decision-making process should start from the anesthesia assessment. If the patient cannot safely undergo a surgical procedure, the sensitivity of the tumor histotype to nonsurgical treatments (chemotherapy, hormonal, immunologic, radiotherapy) is considered. If the tumor does not respond to any form of treatment, the only option for the patient is pain control. Vertebroplasty can be considered for palliative pain control, and the patient should be referred to a pain management specialist.
- Any treatment theoretically determined on a scoring system may not necessarily be applicable and may be “over-ruled” if the ASA⁶¹ score is prohibitive or if there are surgical contraindications for any reason independent from the disease we are dealing with.
- Neurologic compromise present:* If the patient can safely undergo surgery, the first element to be considered is the neurological status. If neurological compromise is present, the possibility of recovery is evaluated on the duration from the onset of symptoms.
- If no neurological recovery of the patient is possible as paraplegia or tetraplegia are present for >48–72 hours, sensitivity to nonsurgical treatments is considered together with surgical stabilization to minimize pain, even for sitting and transfers.

Flowchart 1: Treatment of spinal metastases.

- If the paralysis is incomplete and worsening, emergency decompression and fixation is the recommended treatment of choice.

Neurologic compromise absent: If no neurological symptoms are present, the decision-making process begins by considering the sensitivity to medical oncology treatments and radiotherapy. The local effect of the metastatic deposit in terms of stability must be considered as well.⁴⁹

- If the tumor histotype is not sensitive to radiation nor chemotherapy and the metastasis is solitary, resection of the lesion is proposed. Resection of the tumor may be performed by curettage (debulking, intralesional excision) or en bloc resection. En bloc resection should be performed when extension and location allow feasibility of such treatment⁴³ and for hypervascularized metastases (see Figs. 119.6A to F) as morbidity of intralesional excision due to intraoperative bleeding of vascular metastases can be significant.⁴⁴ The role of stereotactic radiosurgery has similar indications.^{30,62}
- If the metastases are multiple, a surgical plan including both fixation to prevent collapse and decompression

to prevent spinal cord damage is suggested. In case of disseminated disease or if stabilization is not technically feasible, surgical intervention could consider vertebroplasty for pain relief.

- Impending or assessed pathological fracture is decisive in choosing between surgical treatment with decompression and stabilization (see Figs. 119.4A to D) or nonsurgical treatment only. This case is particularly demonstrative of the validity of this algorithm in terms of multidisciplinary approach, by avoiding the morbidity of an en bloc resection, as would be proposed by the Tomita and Tokuiashi scoring systems, while achieving local control of the disease.

This algorithm could represent a valid guide for the decision-making process in the treatment of spine metastases. It is centered on each patient's requirements to allow the best quality of life and is based on a multidisciplinary approach. The proposed algorithm seems effective as an interdisciplinary guidelines.

Prospective studies are necessary to assess the validity, the reliability, and the reproducibility of this algorithm. Furthermore, the continuous progress of medical

oncology and radiotherapy will possibly propose newer, less morbid, and more effective treatments in the future, which can be included in the algorithm.

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KEY POINTS

- The spine is a frequent site of bone metastases from carcinomas. Back pain in a patient with a history of carcinoma warrants investigation to exclude a metastasis. Both quality of life and survival can be seriously threatened by a spine metastasis.
- Magnetic resonance imaging is the imaging technique of choice to evaluate known spine metastasis and detect possible further asymptomatic lesions. Histology, best performed by CT-guided trocar biopsy, is mandatory to diagnosis and, thus, proposes specific treatments. The behavior of metastasis and sensitivity to treatment is related to the primary tumor histotype.
- Surgical options are *palliative procedures* (laminectomy with necessary fixation, fixation alone, vertebroplasty), *debulking* (curettage, intralesional excision), and *en bloc resection*. Minimally invasive techniques are improving functional results while reducing morbidity and pain.
- A multidisciplinary team, including medical oncology, radiation oncology, surgical oncology, and pain management specialist, should be involved in the care of each patient, discussing cost-benefit ratio of possible therapies and evaluating the possibility of combined and staged treatments.
- Scoring systems and algorithms have been proposed to correlate clinical situations and prognosis and guide the treatment to standardize the treatment to obtain the best outcome.

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- A scoring system is proposed based on three prognostic scores: grade of malignancy, visceral metastases, bone metastases. Values are attributed to each, and the addition will suggest the treatment. The tumor extension is graded as well, in order to propose the best surgical technique for the resection.
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The surgeon who first popularized the en bloc resection by posterior approach here describes the original technique. The most important details are: extrapleural release of the vertebral bodies by digital dissection, osteotomy by gigli saw and osteotomes with careful dura protection, posterior fixation based on pedicle screws.

Fisher CG, DiPaola CP, Ryken TC, et al. A novel classification system for spinal instability in neoplastic disease. An evidence-based approach and expert consensus from the spine oncology study group. *Spine*. 2010;35:E1221-9.

This article presents first the Spine Oncology Study Group (SOSG) definition “spine instability” in spine tumors as loss of spinal integrity associated with movement-related pain, symptomatic or progressive deformity, and/or neural compromise under physiologic loads. A scoring system is proposed (Spine Instability Neoplastic Score: SINS) based on patient symptoms and radiographic criteria to predict spine stability of neoplastic lesion. The elements include spinal location of the tumor, type and presence of pain, bone lesion quality, spinal alignment, extent of vertebral body collapse, and posterolateral spinal element involvement. Qualitative scores are assigned based on relative importance of particular factors gleaned from the literature and refined by expert consensus.

Tokuhashi Y, Matsuzaki H, Oda H, et al. A revised scoring system for preoperative evaluation of metastatic spine tumor prognosis. *Spine*. 2005;30:2186-91.

In this article, the scoring system proposed in 1990—based on general conditions, number of extraspinal bone metastases, number of metastases in the spine, metastases to the major internal organs, primary site of the cancer and severity of spinal cord symptoms—is submitted to a revision. More importance is given to the primary site of cancer (0–5 instead of 0–2). The predictivity of the prognosis improved from 62% to 81%. In patients with a total score of 12 or more (predicted survival period 1 year or more), excisional procedures are proposed. In patients with a total score 9–11, excisional procedures are indicated; palliative procedures are suggested in all other cases. Surgery was not indicated in patients with a predicted survival period of 6 months or less (score 0–8).

Intradural Intramedullary and Extramedullary Tumors

Tony Goldschlager, Nicolas Dea

Snapshot

- » Epidemiology
- » Classification
- » Pathology
- » Pertinent Spinal Cord Anatomy
- » Clinical Presentation
- » Syndromes
- » Diagnostic Tests
- » Surgical Treatment

INTRODUCTION

Intradural tumors are among the rarest of neoplastic conditions. Due to the rarity of these tumors, diagnosis and management are challenging. Even for the spine surgeon in a busy center, intradural tumor resection is an infrequent operation, and therefore the potential for research and trials aimed at improving outcomes is especially difficult.¹ Despite this, surgery has the potential to reverse a patient's neurological deficit and offer an oncological cure.

The treatment of intradural tumors combines the best of spine, oncological, and microneurosurgical principles. It requires a team-oriented and multidisciplinary approach involving surgeons, oncologists, neurologists, rehabilitation physicians, radiologists, pathologists, and allied health professionals. Understanding the pathology of each tumor type is especially important in that it guides surgical management in establishing the correct surgical plane, extent of resection, and subsequent adjuvant treatment.

EPIDEMIOLOGY

Spinal cord tumors are rare. They represent only about 0.5% of newly diagnosed tumors¹ and account for 4–8% of all central nervous system tumors.² They have an overall incidence of 0.74 per 100,000 person-years (0.77/100,000

in females and 0.70/100,000 in males). To put this in perspective, the overall cancer incidence in the United States was 423.9/100,000 in females and 556.7/100,000 in males between 2000 and 2004.³ In general, intramedullary tumors are more common in males, whereas intradural-extramedullary tumors are more common in females.⁴ The individual gender distribution for the main tumor subtypes is shown in Figure 120.1.

Approximately two-third of intradural tumors are extramedullary,^{5–7} the most common of which is a meningioma that accounts for 29% of primary spine tumors.⁷ The most common intramedullary tumor in the adult population is an ependymoma that accounts for 23% of primary spine tumors⁷ (Fig. 120.2). Ependymomas have been shown to have an increasing incidence, whereas the incidence of astrocytomas has remained stable.²

CLASSIFICATION

Tumors are classified by their location (Figs. 120.3A to C). This historical classification was based on the findings of myelograms⁸ but is still used today in the magnetic resonance imaging (MRI) era. The first distinction to make is whether a tumor is intradural or extradural in location. If intradural, the next distinction is whether the

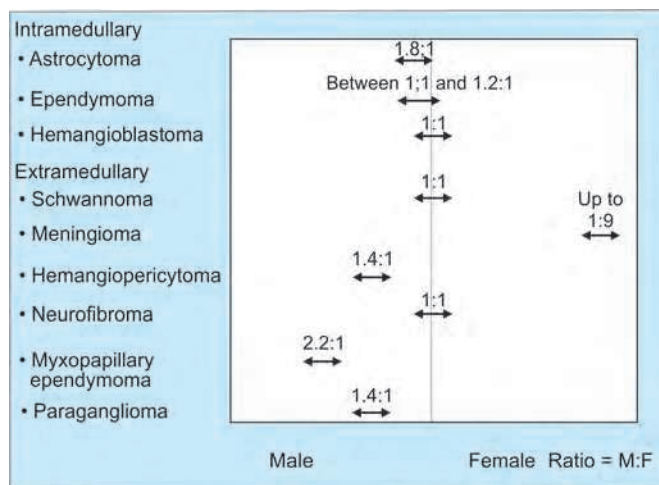


Fig. 120.1: Gender distribution of spinal intradural tumor.

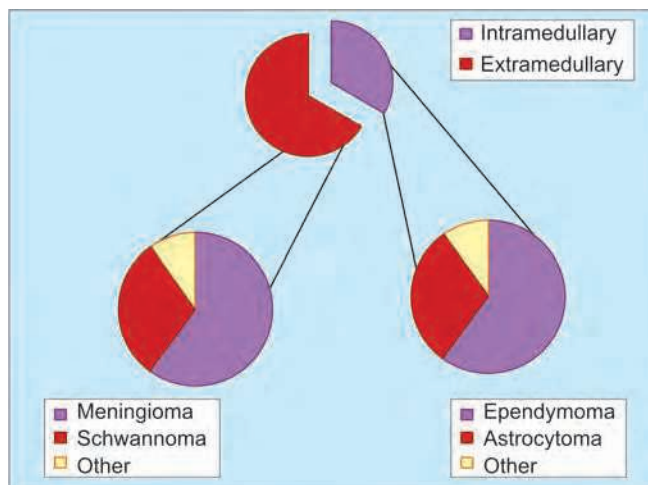
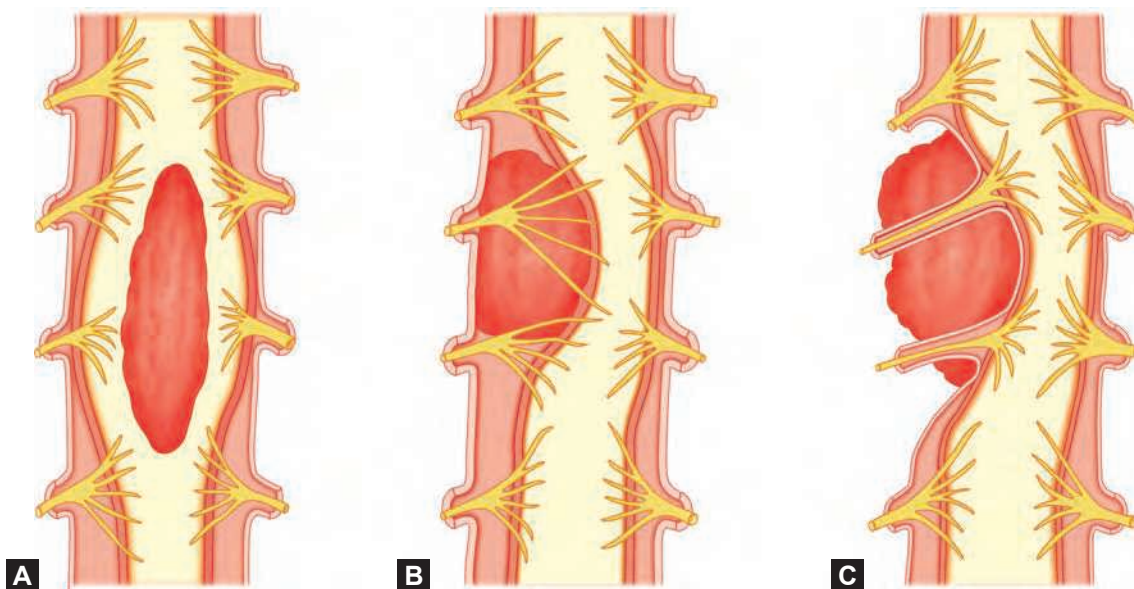


Fig. 120.2: Incidence of tumors by location and pathology.

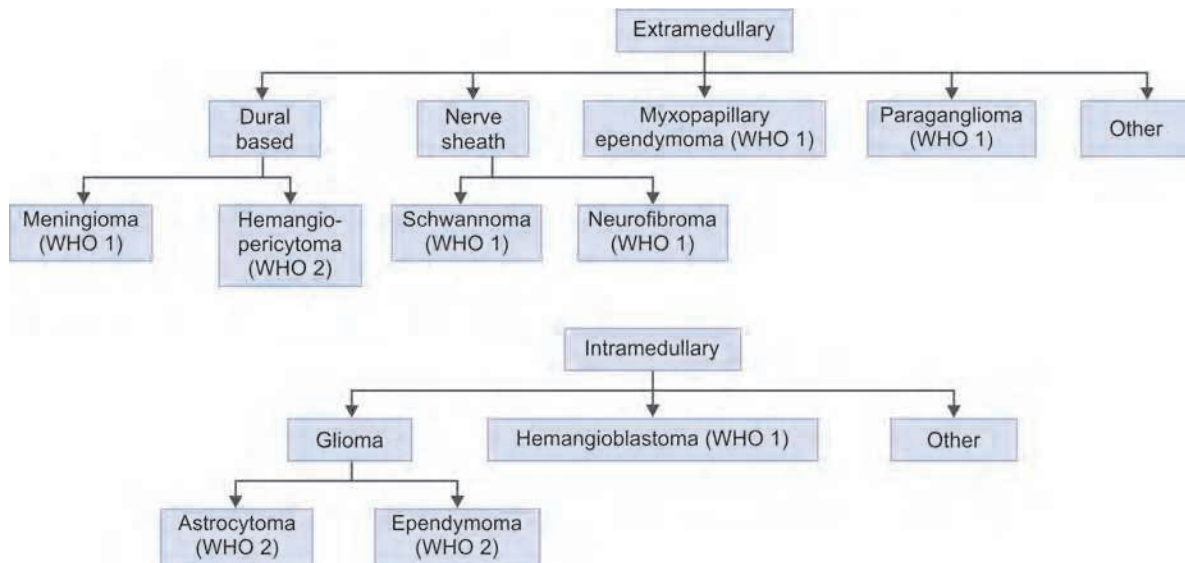


Figs. 120.3A to C: Illustration of (A) intramedullary, (B) intradural extramedullary, and (C) extradural tumors.

tumor is within the parenchyma of the spinal cord, termed *intramedullary*, or external to it, termed *intradural extramedullary*. In some cases, tumors may extend between locations, such as an exophytic tumor of the cord, which may be both intra- and extramedullary; or schwannoma that may be a combination of intradural and extradural as it follows the course of the exiting nerve root. Intradural spinal cord tumors are further classified pathologically (Flowchart 120.1). Accordingly tumors will be discussed below by histopathological subtype.

PATHOLOGY

Understanding tumor pathology provides invaluable information that guides both surgical and postoperative management. The tumor cell of origin will dictate the surgical plane as well as influence the surgical approach and extent of resection. For example, an astrocytic glioma of the spinal cord will more likely be a diffusely infiltrating tumor, without a good surgical plane and hence may not be completely resectable in distinction with an ependymal glioma, which is usually well circumscribed.

Flowchart 120.1: Classification of tumors by location and pathological subtype.

Intradural Extramedullary Tumors

Meningioma

These tumors are dural based, arising from the arachnoid cap cell that is a nonneuroepithelial progenitor cell.⁹ They are most common in the thoracic spine^{9,10} and in females with some series showing a female preponderance approaching 90%.¹⁰ The majority of tumors are benign and characterized as World Health Organization (WHO) grade 1; however, atypical (WHO grade 2) and anaplastic (WHO grade 3) tumors occur and show a male predominance.

There are nine histomorphological subtypes of WHO grade 1 meningiomas, which accounts for their diverse appearance. These are meningothelial, fibroblastic, transitional, angiomatous, microcystic, lymphoplasmacyte-rich, secretory, metaplastic, and psammomatous. The latter is the most common in the spine and is characterized by frequent psammoma bodies. These are irregular-shaped collections of osteoid that can become confluent and calcify and occasionally form bone.¹⁰ While calcification is common microscopically and can be detected radiologically if sufficiently abundant, grossly calcified meningiomas occur only in up to 5% of cases.¹¹ Another typical histological feature is that of whorl formation of the intervening neoplastic cells.

The presence of certain histological features including increased mitotic activity can upgrade the tumor grade to

atypical or WHO grade 2. Chordoid and clear cell variants are automatically assigned a grade 2. Obviously malignant cytology, or a marked increase in mitotic activity or papillary or rhabdoid subtypes, designates a meningioma as malignant¹⁰ (WHO grade 3). Proliferation indices have been shown to correlate with tumor growth.¹⁰ Immunohistochemical staining is invariably positive for EMA, however, with decreasing reactivity in higher-grade tumors.¹⁰

Meningiomas commonly are positive for sex hormone receptors: 88% have progesterone, 40% estrogen, and 39% androgen receptors.¹⁰ The presence of estrogen receptors may be associated with aggressive histological characteristics.¹²

Meningiomas typically have aberrations involving chromosome 22¹³ and are a hallmark feature of neurofibromatosis type 2 (NF2) whose locus is located on chromosome 22q.¹⁰ Apart from neurofibromatosis, there are other familial conditions in which patients develop multiple meningiomas, and in these the SUFU mutation has been implicated.¹⁴ Other affected genes in meningioma include 1p, 14q¹³ and DAL.¹⁰

Radiation-induced meningiomas are the most common form of radiation-induced neoplasms.¹⁵ These tumors tend to be more histologically aggressive and associated with chromosomal aberrations in particular at loci 1p and 6q.¹⁰

Hemangiopericytoma

Hemangiopericytomas are radiologically similar but histologically distinct to meningiomas. They therefore present

a common radiological differential diagnosis to meningioma, although they occur much more rarely.¹⁶ They are mesenchymal cell tumors composed of a highly cellular and vascular stroma with characteristic “Staghorn” appearance of vasculature.¹⁰ Hemangiopericytoma are a locally aggressive tumor with a propensity for recurrence and are classified as WHO grade 2.¹⁶

Peripheral Nerve Sheath Tumors

There are two main types of peripheral nerve sheath tumors: schwannomas and neurofibromas. The main distinction is that schwannomas arise from and contain neoplastic Schwann cells, whereas neurofibromas may contain all the elements of a peripheral nerve, including perineural cells, axons, fibroblasts, and Schwann cells.¹⁷ These tumors arise from the nerve root before leaving the dural sac in 60–80% and a further 10% arise from the nerve as it exits the dural sac in its nerve sleeve.¹⁸ This may give rise to dumbbell morphology that has been classified based on location.¹⁹ Schwannomas usually arise from the dorsal sensory part of the nerve root.²⁰

They are both graded as WHO grade 1 tumors. However, malignant peripheral nerve sheath tumors occur in a few cases.¹⁸ They account for about 5% of soft-tissue tumors.¹⁰ The majority arise from neurofibromas; about half from plexiform neurofibromas in patients with neurofibromatosis type 1, but they may also arise de novo.¹⁰ Very rarely do they arise from the malignant transformation of a schwannoma.^{10,17}

Schwannoma

This is a well-encapsulated tumor that arises from neoplastic Schwann cells.¹⁰ It is characteristically composed of two distinct patterns known as Antoni A and B. Areas of densely packed cells with areas of cellular palisading are the Antoni A pattern, whereas loosely arranged cells often with intervening lipid are the Antoni B pattern. The Antoni A palisading pattern often forms a characteristic Verocay body that resembles the wooden spindles used in textile spinning.¹⁷ The preponderance of Antoni A relative to B shows both inter- and intratumor variability. Cellular schwannomas are a histological variant composed of predominantly Antoni A regions, typically lacking Verocay bodies.¹⁰ This variant has a higher recurrence rate.¹⁰ Immunohistochemistry is typically positive for S100 and Leu 7.¹⁰ Inactivating mutations within the NF2 gene are found in up to 60% of schwannomas.¹⁰

Neurofibroma

These tumors contain a combination of nerve fibers, collagen fibers, fibroblasts, and Schwann cells.¹⁰ The latter typically being smaller than the Schwann cells found in schwannomas. Collagen fiber appears variably, but typically they give a “shredded carrot” appearance.¹⁰ Blood vessels within neurofibromas typically are not hyalinized, unlike in schwannomas.¹⁰ They also contain less basement membrane proteins²¹ than schwannomas reflecting less immunohistochemical expressivity for such markers as well as S100.

Myxopapillary Ependymoma

This tumor is almost exclusively localized to the region of the termination of the spinal cord, specifically in the filum terminale, conus medullaris or cauda equina. It is a slow-growing tumor, classified as a WHO grade 1 tumor, and typically occurs in young adults with a 2.2:1 male to female ratio.¹⁰ Patients therefore typically present with insidious onset of back pain and may have mixed upper and lower motor neuron signs as well as bowel, bladder or sexual dysfunction.

Histologically, it is characterized by columnar or cuboidal cells arranged with papillary architecture, containing a mixoid stroma that typically stains with alcian blue. It is generally positive for glial fibrillary acidic protein (GFAP) and S100 immunohistochemical stains but negative for cytokeratin.¹⁰

Paraganglioma

Paraganglioma is a neuroendocrine tumor, arising from neural crest cells. It uncommonly occurs within the spine but has a predilection to the cauda equina region. They, however, only account for around 3.5% of tumors in this region. They have a 1.4:1 male to female ratio. Histologically they are composed of type 1 or Zellballen cells, surrounded by a layer of sustentacular, type 2 cells. There are only case reports of endocrinologically active cauda equina paragangliomas.¹⁰

Metastasis

Intradural metastases are rare. The vast majority of spinal metastatic disease originates from the vertebral bodies and is thus extradural. Intradural metastatic disease may either be extra ($\approx 4\%$) or intramedullary ($\approx 2\%$). The pattern of transmission may either be direct extension, haematogenous or via the cerebrospinal fluid (CSF), causing the so-called drop metastasis. Primary intracranial tumors can metastasize to the lumbar cistern that way.

Intramedullary Tumors

Glioma

Glial cells are the supporting cells of the central nervous system and are composed of ependymal cells, astrocytes, and oligodendrocytes. Tumors can occur from any of these cell types; however, the latter rarely occurs in the spinal cord.^{10,22}

Astrocytoma

Astrocytomas originating in the spinal cord increase in tumor grade much less frequently than their cranial counterpart:²³ 75% are low grade (WHO grade 2)^{24,25} of which the diffuse fibrillary type is the most common.²⁵ Pilocytic astrocytoma (WHO 1 grade) accounts for 11% of pediatric spinal cord tumors.¹⁰ It is characterized by cyst formation containing a biphasic pattern of cells with compact bipolar cells associated with Rosenthal fibers and loose textured multipolar cells with microcysts.¹⁰ Rosenthal fibers are corkscrew-shaped intracytoplasmic inclusions.²⁶ Diffuse astrocytoma is characterized by neoplastic fibrillary astrocytes with nuclear atypia but the absence of mitosis. They may contain reactive gemistocytic astrocytes and microcysts.¹⁰ Their borders are difficult to delineate unlike pilocytic astrocytomas.²⁷ The malignant variant anaplastic astrocytoma, WHO grade 3, and glioblastoma WHO grade 4 account for up to 15–1.5% of tumors respectively⁸ and have a very poor prognosis.²³ Immunohistochemical staining is consistently positive for GFAP.¹⁰ TP53 mutations are a genetic hallmark of astrocytoma and are present in >60% of cases.¹⁰

Ependymoma

Ependymomas are typically slow growing and composed of neoplastic ependymal cells with well-demarcated borders. They are the most common histological subtype of intramedullary tumors in adults. They are most common in the cervical spine.²⁸ Some sources report an equal distribution between males and females,¹⁰ whereas others show a predilection for males.² They are typically classified as WHO grade 2 tumor; however, there is a rare anaplastic form that is graded as WHO grade 3. There are four histological subtypes—cellular, papillary, clear cell, and tanyctic; the latter being most prevalent in the spine.¹⁰

Ependymomas are characterized histologically as a cellular glioma with monomorphic nuclei. There may be

salt-and-pepper speckled chromatin and mitosis are rare or absent.¹⁰ A classic but rare feature is that the cells are either arranged in ependymal rosettes, with a tubular lumen,²⁹ or perivascular pseudorosettes; however, these are particularly rare in the tanyctic variant.¹⁰ Tanyctic ependymomas have cells arranged in fascicles that in some cases can be difficult to distinguish from astrocytomas. Immunohistochemistry will typically be positive for GFAP, S100, and vimentin as well as EMA in many cases.¹⁰ Ependymomas are a common manifestation of patients with NF2. There was thought to be an association with SV40 virus although this remains uncertain.¹⁰ The most common genetic aberration is on chromosome 22 in up to 30% of cases. MDM2 amplification is common in adult ependymomas.¹⁰

Hemangioblastoma

Hemangioblastomas are characteristically vascular tumors, often partially cystic with a mural nodule. The cell of origin remains elusive;¹⁰ however, vascular endothelial growth factor plays a role in tumor genesis.³⁰ They occur sporadically but are associated with Von Hippel-Lindau disease in 25% of cases.¹⁸ Histologically they are composed of lipid laden cells surrounded by a vascular network. Rosenthal fibers can be seen and necrosis is rare. Immunohistochemistry is positive for neuron-specific enolase and vimentin.³⁰

Other Rare Neoplasms

Ependymoma and astrocytomas comprise the overwhelming majority of spinal cord gliomas; however, rarely gangliogliomas and oligodendrogliomas can occur. These account for <1% and <50 cases, respectively.⁸ The first line of treatment for both is surgical resection.

Primary central nervous system lymphoma is also rare accounting for <1% of spinal cord tumors. They are typically B cell lymphomas. Diagnosis may be obtained by CSF cytology or biopsy. Treatment is nonsurgical with dexamethasone, methotrexate, and radiotherapy. Prognosis is poor.⁸

Dermoids, epidermoids, teratomas, and lipomas complete the differential diagnosis. Although often extramedullary, intramedullary extension at the level of the conus is not infrequent. Non-neoplastic lesions that could be mislabeled for tumors include vascular lesions (arteriovenous malformations, cavernomas), demyelinating diseases, and infections.

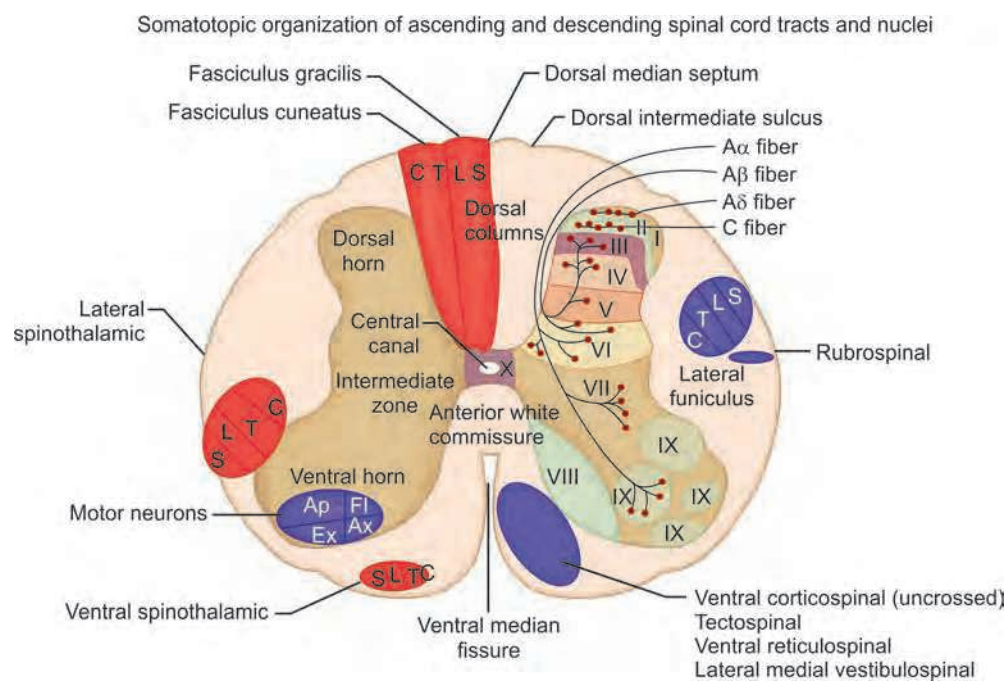


Fig. 120.4: Cross-sectional diagram of the spinal cord.

PERTINENT SPINAL CORD ANATOMY

The spinal cord begins caudal to the medulla oblongata, at the point where the first cervical nerve roots emerge,³¹ and ends as the conus medullaris, typically at L1-L2. In cross-section, the spinal cord contains a central H-shaped area of grey matter arranged in anterior, posterior, and lateral horns that are further subdivided into groups known as the lamina of Rexed³² (Fig. 120.4). Within the center of the grey matter is the central canal that is lined with ependyma being continuous with the cranial ventricular system. Surrounding the central grey matter is the white matter within which run the ascending and descending tracts. Understanding the arrangement of these tracts and their somatotopy is crucial as it explains the clinical presentation of tumors and safe surgical corridors to facilitate their resection. The following points will aid in understanding some of the clinical syndromes discussed later. The somatotopy of the motor or corticospinal tracts is such that the upper extremity tracts lie medial to the lower extremity. The anterior horn cell, from which the motor nerve emerges, is the point at which the manifestations of dysfunction change from upper to lower motor neuron. As the sensory nerve enters the dorsal horn, fibers that carry pain, temperature, and light touch decussate before ascending in the spinothalamic tracts. Those fibers that contain the modalities of deep touch and proprioception ascend uncrossed in the dorsal columns.

CLINICAL PRESENTATION

Tumors typically present in an indolent fashion. In rare situations, they can present with rapid or sudden deterioration, which may be due to tumor hemorrhage or cord infarction.^{33,34} Like with an intracranial mass lesion, the manifestations of spinal cord compression are proportional to both the size and rate of growth of a tumor.

Patients typically present due to either pain or loss of function, pain being the most common presentation.^{5,35} Once they do present, however, misdiagnosis of spinal cord tumors is unfortunately not uncommon.³⁶ It is important that the assessing physician has an index of suspicion for this rare condition. Differentiating intramedullary from extramedullary tumors may be difficult clinically but distinguishing features are shown in Table 120.1.

Patient evaluation should include assessment of the following:

1. **Pain:** Pain is the most common presenting symptom of an intradural tumor.³⁵ There are different types of pain that a patient may experience, including axial, radicular, central and in some cases distant pain such as headache.^{37,38} The character of the pain may provide a distinguishing clue to the clinician from the substantially more common type of back pain that results from degenerative disease. Pain may be worse at night or during recumbence unlike mechanical pain

Table 120.1: Distinguishing features of intramedullary from extramedullary tumors.

<i>Signs and symptoms</i>	<i>Intramedullary tumors</i>	<i>Extramedullary tumors</i>
Pain	Less common, and if present more likely funicular pain	Pain more common and often radicular in nature
Neurological signs	Lower motor neuron signs at the level of lesion (due to the involvement of anterior horn cells); upper motor neuron signs caudal to lesion	Upper motor neuron signs early due to extrinsic compression
Paresthesia	Ascending progression	Descending progression
Bowel/bladder	Dysfunction more common especially with conus lesions	Unusual

that is worse on movement. This may be due to venous congestion or dural distension, which is increased during recumbency. Another possible explanation is that the normal serum cortisol nadir at night results in increased tumor swelling. Patients may experience radicular pain due to tumor involvement of a nerve root. This pain may have dysesthetic qualities or be thoracic in location, both of which are rare in the initial presentation of radicular pain from disc disease. In some cases, such pain may manifest as intercostal or chest pain,³⁹ leading to pulmonary or cardiac investigations. Central pain, also called funicular pain, is a deep, poorly localized pain resulting from irritation of the spinothalamic or dorsal column fibers. It may be burning in nature with occasional stabbing like qualities. Such pain is indicative of spinal cord pathology such as an intramedullary tumor. Headaches can manifest from intradural tumors for a variety of reasons. They may be cervicogenic resulting from an upper cervical tumor that irritates the dura or nerve roots. They can result from changes in CSF dynamics⁴⁰ either from obstruction, such as from a foramen magnum tumor, or from increase in CSF protein, such as from a distant intradural tumor like a lumbar schwannoma.⁴¹ Patients with hydrocephalus will typically have morning headaches with associated nausea and vomiting. Rarely, elderly patients may present with the symptoms of normal pressure hydrocephalus, including gait disturbance, dementia, and urinary incontinence.⁴²⁻⁴⁴

2. **Function:** Weakness can be a manifestation of myelopathy, radiculopathy or a combination of both. A tumor causing myelopathy will typically produce weakness when there is dysfunction of >50% of upper motor neurons,³⁸ hence on presentation patients may have only subtle findings. Patients may present with difficulty ambulating due to proprioceptive dysfunction^{8,35,36} but have normal motor strength on examination, highlighting the need for thorough neu-

rological assessment.³⁶ In about 13% of patients, bowel or bladder dysfunction was the mode of presentation.¹⁴

3. **Neurological examination:** The neurological assessment is aimed at determining both the level of dysfunction and differentiating upper from lower motor neuron dysfunction. Longitudinal localization of the tumor is achieved by ascertaining the last level of normal function. Compartmental localization of the tumor is much more difficult and is confirmed by MRI. Suggestive features of intramedullary versus extramedullary tumors are in Table 120.1.

SYNDROMES

Anterior Cord

This syndrome spares the dorsal columns, hence, the patient will have a dissociated sensory loss, and specifically there will be motor weakness with loss of pain and temperature sensation but preservation of proprioception and vibration sensation. This syndrome can occur with ventral meningiomas or ventrally located intramedullary tumors. It occurs in its purest form with anterior spinal artery infarction.

Central Cord

This syndrome is most typical in cervical pathology and characterized by a preferential loss of upper extremity, especially hand motor function, with relative preservation of lower extremity function. This is due to the medial somatotopy of the upper extremity corticospinal tracts. It is most likely to occur with ependymoma or with tumor-associated syrinx. It also happens in trauma typically from hyperextension injuries.

Posterior Cord

This syndrome is due to dorsal column dysfunction resulting in a sensory and proprioceptive deficit. Despite

motor preservation, patients often have difficulty ambulating due to impaired proprioception. Patients who have dorsally located tumors may present with this syndrome, as will patients who have undergone a dorsal midline myelotomy.

Brown Sequard

This syndrome is classically due to hemisection of the spinal cord, which causes ipsilateral weakness and proprioceptive loss and contralateral pain and temperature loss. This is due to loss of the corticospinal and dorsal column tracts ipsilaterally and the spinothalamic tracts that decussate, respectively. Tumors involving the cord asymmetrically can produce these signs to a varying extent.

Conus Medullaris or Cauda Equina

Symptoms resulting from lesions of the cauda equina tend to have a more gradual onset compared with those originating in the conus.³² Pain is a prominent feature in cauda equina lesions and is often radicular in nature.³² Patients with lesions of the conus will more likely have bowel or bladder dysfunction and saddle paresthesia. They may have a more symmetric pattern of symptoms and dissociated sensory loss. Lesions of the conus may produce mixed upper and lower motor neurons signs with a preserved knee jerk reflex. The ankle jerk reflex is often absent from lesions in either location.

Other Clinical Features

It is rare for patients with primary tumors to present with constitutional features such as fatigue and weight loss; when present, this may be suggestive of a metastatic process.

Changes in spinal alignment manifested by loss of lordosis, scoliosis or torticollis may be apparent in up to one-third of patients with intramedullary tumors.⁴⁵ Horner's syndrome may be present, if the lateral horn cells in the cervicothoracic region are affected by a tumor.⁴⁵

Part of the assessment should include a review for manifestations of syndromes such as neurofibromatosis type 1. This includes a positive family history and a search for café-au-lait spots, neurofibromas, freckling of the armpits or groin, lisch nodules (iris hamartomas) as well as obtaining other imaging for optic nerve gliomas, sphenoid dysplasia, and plexiform neurofibromas.⁴⁶

DIAGNOSTIC TESTS

Plain radiographs may provide a clue to underlying pathology within the cord. There may be bony remodeling or reduction in the size of a pedicle from a peripheral nerve sheath tumor or the spinal canal may be enlarged at the level of a tumor. Radiographs may assist in operative planning; however, MRI should be performed in all cases as it provides the highest resolution imaging of the tumor and the spinal cord itself.

Historically, two lumbar puncture-based tests were used that are now largely replaced by imaging. It should be noted that lumbar puncture might be contraindicated, if there is an obstructive tumor, particularly at the craniocervical junction. Froin syndrome is viscous, proteinaceous, and hypercoagulable CSF due to stagnated CSF below the site of an obstruction.⁴⁷ Queckenstedt maneuver is performed by measuring CSF pressure and then by occluding the jugular veins, which will lead to a sharp rise in CSF pressure in the normal state; in cases where there is an obstruction, this rise will not occur.⁴⁸

Magnetic resonance imaging is the investigation of choice for evaluation of intradural tumors.²⁰ The first step in interpretation is to distinguish whether the tumor is intra- or extramedullary. An extramedullary tumor lies between the dura and the spinal cord and hence displaces the spinal cord; there will be a sharp interface with the CSF and an enlarged CSF space on the tumor side. The distinguishing features of common extramedullary tumors are shown in Table 120.2.

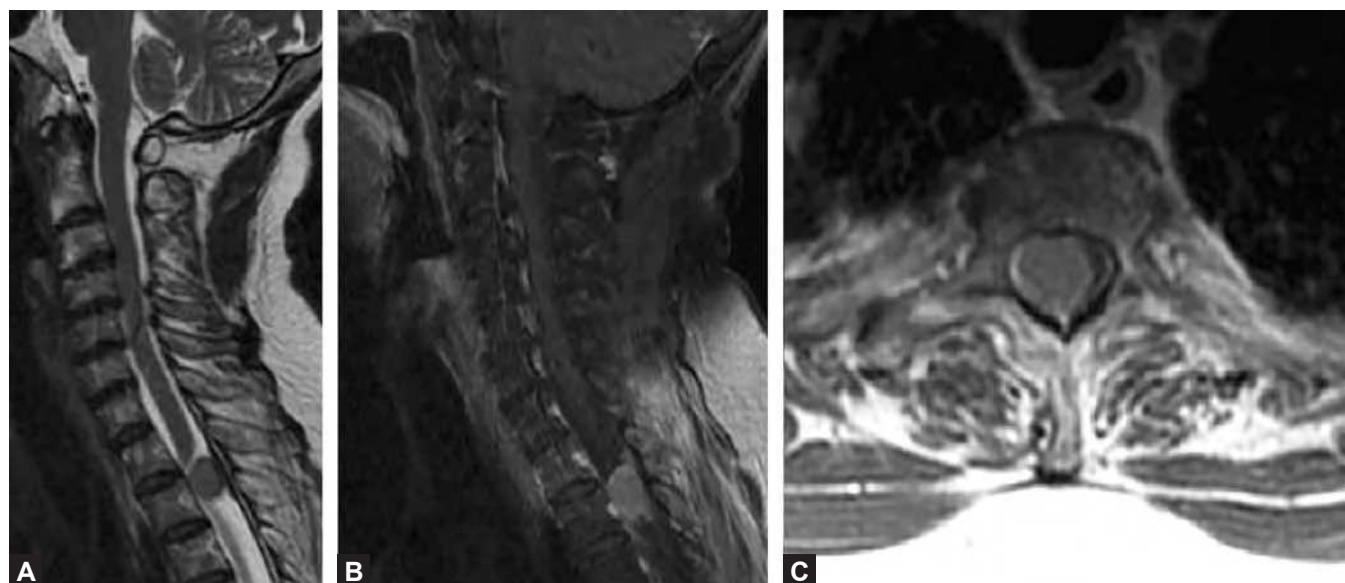
Meningiomas are most frequent in the older female population and are most commonly located in the thoracic spine. They are typically homogeneously enhancing, and may have foci of calcification and a dural tail (Figs. 120.5A to C). Nerve sheath tumors more commonly occur in the lumbar spine and may have a dumbbell appearance as they follow the course of the nerve root. They may be cystic and are more typically heterogeneously contrast enhancing (Figs. 120.6A to C). There may be remodeling of surrounding bone such as scalloping of the vertebral body, enlargement of the foramen or reduced pedicle size all of which are best appreciated on CT scan. Myxopapillary ependymomas are located at the conus region and may be hard to differentiate from a nerve sheath tumor (Figs. 120.7A to C).

Intramedullary tumors occur within the cord parenchyma and typically cause expansion of the cord. There may be an associated cord edema and syrinx particularly in the case of ependymomas. Ependymomas are the most com-

Table 120.2: MRI features of intradural extramedullary tumors.

Feature	Schwannoma	Meningioma
Incidence of spinal cord tumors	About 26%	About 32% (more common in female, and patients >60 years of age)
Location	Lumbar	Thoracic
T1 signal	Isointense	Hypoiso-intense
T2 signal	Markedly hyperintense	Hyperintense
Enhancement pattern	Heterogeneous	Homogeneous
Calcification	Rare	Common
Shape	Dumb-bell	Round
Other	May be cystic, have a foraminal or extradural component with bony remodeling best seen on CT	Dural tail

(MRI: Magnetic resonance imaging; CT: Computed tomography).



Figs. 120.5A to C: Typical appearance of a spinal meningioma.

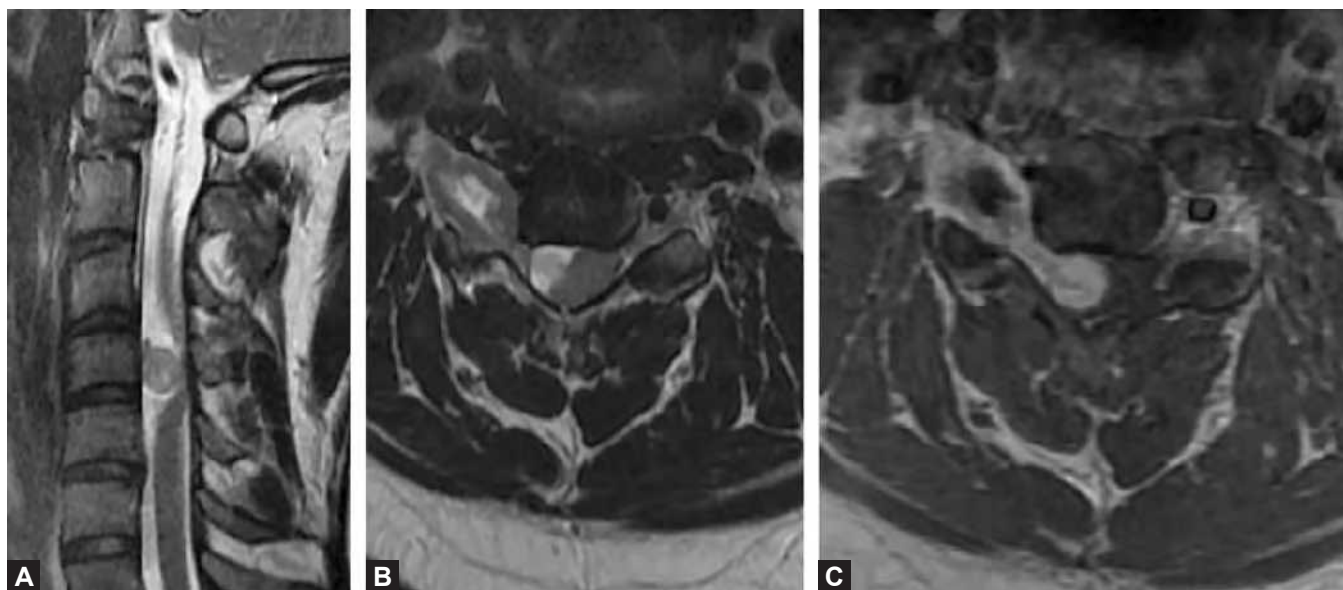
mon intramedullary tumor and more frequently centrally located due to their origin from the ependymal lining of the central canal. They may have surrounding hemosiderin and are typically well demarcated, as are hemangioblastomas. Astrocytomas are in contradiction typically poorly demarcated and show heterogeneous contrast enhancement. Distinguishing features are shown in Table 120.3.

Imaging the entire neuro-axis may be required, especially when a drop metastases is considered. Patients with tumors that are associated with familial conditions, such as neurofibromatosis or Von Hippel-Lindau syndrome, will require imaging to exclude the other disease-specific manifestations.

■ SURGICAL TREATMENT

Indications for Surgery

Surgery is indicated for one or more of the following reasons: to achieve neurological decompression, obtain a tissue diagnosis or for oncological resection. The advent of MRI may have led to an increase rate of detection of tumors.² The decision to operate needs to be weighed up with the natural history of the individual tumor. There is, however, limited literature on the natural history of these tumors. Ozawa showed that for intradural-extradural tumors, meningiomas were more likely to grow and eventually require resection than schwannomas.⁴⁹ The



Figs. 120.6A to C: MRI appearance of a dumbbell schwannoma.



Figs. 120.7A to C: MRI appearance of a filum terminale myxopapillary ependymoma.

decision of whether and when to operate needs to be tailored to the individual patient and tumor type. In asymptomatic patients, diagnostic ambiguity, development of symptoms, and tumor growth on imaging are factors that suggest surgical intervention. Otherwise, it is acceptable to follow an asymptomatic intradural tumor, especially when the radiologic features are consistent with a known tumor

pattern. Another consideration is that smaller tumors are easier to resect.⁴⁹

Establish Surgical Aims

Prior to surgery, all available information should be reviewed and studied. Although the diagnosis is not certain

Table 120.3: MRI features of intradural intramedullary tumors.

Features	Ependymoma	Astrocytoma	Hemangioblastoma
Incidence of intramedullary tumors	60%	30%	Up to 8%
Location	C > T > L	C>T (usually <4 segments)	C>T (dorsally located in >90% of cases)
T1 signal	Iso	Hypointense	Iso
T2 signal	Slightly hyper	Hyperintense	Hyper
Enhancement pattern	Most enhance homogeneously	Often enhance, usually heterogeneously	Usually enhance, may have enhancing mural nodule
Associated cyst/syrinx	More likely	Less likely	Often have a cyst, syrinx is uncommon
Demarcation	Clear margin in most	Poor demarcation in most	Clear margin in most
Hemorrhage	May have hemosiderin ring or hemorrhage “cap sign”	Rare	Flow voids, serpentine vessels
Other	Most central	More eccentric	Look for other manifestations of Von Hippel-Lindau

(MRI: Magnetic resonance imaging).

until pathological confirmation, the imaging will provide a high likelihood of the individual tumor type and specific surgical complexities associated with it. Options on surgical approach, extent of resection, degree of aggressiveness of surgery and contingency plans need to be considered. The surgeon should take into account both tumor and patient factors, present options to the patient, and consider the patient's wishes. Comprehensive discussions with the patient preoperatively are required to prepare the patient and give realistic expectations. From a symptom point of view, the main aim of surgery is to stabilize neurology. For intramedullary tumors, it is not uncommon for patients to experience worsening of neurological function postoperatively, at least transiently. It is useful to review imaging at rounds, tumor board meetings, with colleagues or neuro-radiologists. This may provide additional insights that are valuable in surgical planning.

Preoperative Considerations

Surgical Approach

The surgical approach is dictated by specific anatomy of tumor. For the majority of tumors, even if located ventrally, a standard posterior laminectomy or posterolateral approach will suffice; however, an anterior approach remains an option particularly in the subaxial cervical spine.⁵⁰ Spinal stability needs to be considered, and if wider exposures are required there may be a need for stabilization.

Anesthetic Considerations

The surgeon and anesthesiologist should discuss the important aspects of the surgery ahead of time. Neuroprotective measures, such as administration of dexamethasone and maintenance of normotension, are standard considerations but especially pertinent to tumors causing spinal cord compression or raised intrathecal pressure. If neurophysiological monitoring is to be used, the anesthetic may need to be tailored to accommodate this, e.g. by avoiding neuromuscular blockade. Cervical tumors may produce postoperative respiratory difficulties that may require intensive care unit.

Tumor Localization

Tumor localization can be a challenge, particularly in the thoracic spine. It is often beneficial to obtain plain radiographs for evaluation of anatomical anomalies, such as transitional or additional vertebrae; such findings potentially confuse intraoperative localization if not previously identified. These findings may be missed on an MRI. In some cases, radiolucent features that succor localization may be seen on a radiograph, such as tumor calcification or remodeling of surrounding bone. Radiological-guided skin marking can also assist; however, it is important to ensure that patient positioning during the localization mimics the operative position to reduce skin distortion.⁵¹ Navigation is used increasingly in spine surgery for instru-

mentation; however, the ability to merge soft tissue with bony imaging within the spine, as is done for brain tumors, to assist with tumor localization and guide resection is not yet available.⁵²

Equipment

The need for neurophysiological monitoring, image guidance, spinal instrumentation, intraoperative ultrasound and other useful adjuncts needs to be considered and organized preoperatively.

Neurophysiological is used routinely in some centers and has been shown to have a role in predicting postoperative deficit and recovery;^{7,53} however, it has not been proven to prevent deterioration.⁵⁴ Despite this, it is considered an extremely useful tool that provides real-time feedback during surgery.^{7,53,55} Monitoring options include evoked potentials—both sensory and motor that are useful for lesions around the spinal cord and free-running electromyography for lesions around nerve roots with or without stimulation. It is recommended that monitoring continue throughout the whole case, as late changes may occur following tumor resection; these may necessitate alternate measures such as duroplasty.⁵³

Intraoperative ultrasound is a useful adjunct providing real-time imaging of the lesion and its relation to the neural elements.^{56,57} It is especially useful for confirming adequacy of the surgical corridor.⁵⁸ We recommend its use following the laminectomy, prior to the durotomy.

Surgical Procedure

Following endotracheal intubation, insertion of arterial lines and urinary catheter, the patient is positioned prone in the military position. Prophylactic antibiotics and dexamethasone are administered. Neurophysiological monitoring is attached. Care is taken to ensure that the neck is gently flexed and the spine is straight and not rotated. The Mayfield skull clamp secures the head and neck in cervical and upper thoracic cases; however, we recommend it to use in all cases as it reduces pressure to the eyes and facial pressure sores, although it does not prevent ischemic optic neuropathy.⁵⁹ All pressure areas are protected and deep venous thrombosis prophylactic measures ensured. The surgeon encircles the table to recheck the aforementioned factors. The appropriate level is marked, and sterile prep and draping are performed in the usual manner. Local anesthetic is infiltrated and a midline incision is then

made. Subperiosteal dissection is performed to expose the appropriate laminae. Level reconfirmation is recommended prior to performing standard laminectomies. The intraoperative ultrasound is used to confirm the location of the tumor and that the laminectomy provides adequate exposure both in the rostral and caudal directions.⁵⁸ Once the exposure is adequate, care is taken to ensure adequate hemostasis from the bone edges and epidural veins. Irrigation is used to remove bone dust and debris. Bone wax is used on the laminectomy kerf and hemostatic agent, such as gelatin sponge, packed laterally at the bone dural interface. The microscope is brought in and the microinstruments made accessible. A midline durotomy is then made and the arachnoid opened allowing for CSF drainage. Hitching sutures are then used to retract the dura laterally and care taken to prevent blood run in, maintaining a bloodless intradural field.

Intramedullary Tumor Resection

Using the microscope, the spinal cord is inspected; the tumor may be obvious on the cord surface or an expanded cord may be noted. The overlying pial blood vessels are sometimes suffused. If necessary, the dentate ligament can be focally divided to allow for gentle rotation of the cord. The intraoperative ultrasound may be useful at this stage to delineate the tumor and assess where it is closest to the surface of the cord.

A myelotomy can be performed through one of four locations—dorsal midline, the dorsal root entry zone on either side or where the tumor presents itself to the surface. The most typical site for the majority of tumors is a dorsal midline myelotomy. Ventrally located tumors such as hemangioblastoma that present to the cord surface have been approached from anterior.⁶⁰ A ventral myelotomy is not recommended due to disruption of the anterior corticospinal and spinothalamic tracts.⁶¹ For ventral or eccentric tumors, a myelotomy through the dorsal root entry zone remains an option in select cases.⁶¹

Following myelotomy, the tumor is inspected with particular reference to its surgical plane. Resection technique is tailored to the tumor using standard microneurosurgical principles. The tumor is dissected from the cord and not the cord from the tumor. To avoid excessive manipulation of the cord, it is often advisable to debulk the tumor first. An ultrasonic aspirator is an invaluable tool for this. Alternatively, a side-cutting aspirator can be used as it offers the advantage of having a low profile with a side cutting port

providing superior visualization and it does not produce heat.⁶²

Ependymomas and hemangioblastomas are typically well circumscribed and have a good plane; this is less frequently the case with astrocytomas. If a poorly demarcated tumor is encountered, it may well be a diffusely infiltrating glioma, and the decision to biopsy alone should be strongly considered. Frozen section may be helpful, especially if it reveals a high-grade malignancy; however, the decision on the extent of resection depends mainly on the surgical circumstances and perceived safety of resection. Maintaining the tumor-pial plane and avoiding entry into the tumor are especially important for hemangioblastoma resection. These tumors are highly vascular and systematically cauterizing its blood supply circumferentially is required.

Following tumor resection, the tumor bed is irrigated and inspected to ensure hemostasis. It is advisable to minimize retention of hemostatic agents within the cord if possible. Standard watertight dural closure is then performed; however, if there are concerns of cord swelling or impairment of normal CSF flow around the cord an expansion duroplasty should be considered. A valsalva maneuver can be employed to exclude CSF leak from the dural closure. Fascial and skin closure should be performed in a watertight fashion as well.

The patient is typically nursed recumbent for 24–48 hours and then elevated as tolerated by low-pressure symptoms. The wound should be frequently checked for CSF leak. A postoperative MRI may be performed as a baseline and then should subsequently be performed to monitor for recurrence at increasing intervals.

Intradural Extramedullary Tumor Resection

The location of the dural attachment of meningioma is shown in Figure 120.8. The surgical approach is usually posterior⁶³ even for ventral tumors.⁶⁴ The location of the dural attachment should be identified and, if possible, dealt with first as this will reduce the tumor blood supply. There is considerable debate as to the extent of dural resection. Radiological studies have failed to predict dural invasion preoperatively.^{65–67} Some studies have concluded that a Simpson⁶⁸ grade 2 resection with coagulation of the dura is sufficient and the added risk of dural resection unnecessary.^{63,69,70} However, others have shown no recurrence in Simpson grade 1 resection and advocate this when feasible, particularly in younger patients.⁶⁷ The overriding principle in meningioma resection, as with any

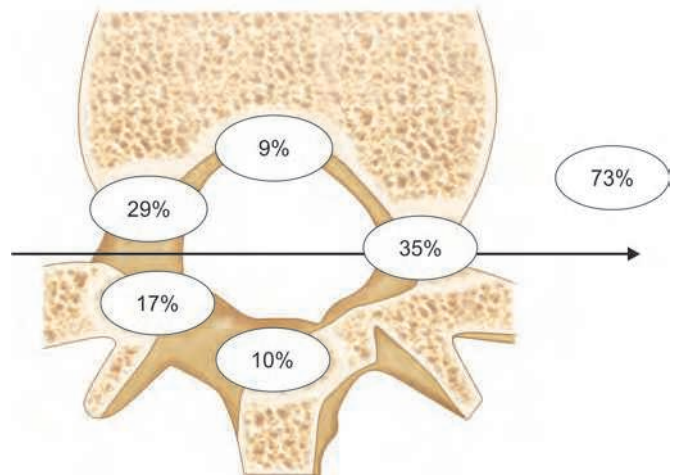


Fig. 120.8: Location of dural attachment of spinal meningiomas.⁷⁰

other tumors, is to avoid pressure on the cord. The dentate ligament can be divided, which allows for gentle rotation of the cord to facilitate greater exposure of the tumor. Internal debulking of the tumor is often a necessary step to reduce its size and aid removal without cord manipulation. Extensive calcification is an independent risk factor for complications,⁷⁰ but careful use of the ultrasonic aspirator with specific attachments for calcified tumors may aid in debulking.

For nerve sheath tumors that require more extensive bony removal, segmental instrumentation may be required. Identifying the proximal and distal nerve fascicle is an important first step, and then the tumor can usually be dissected free from the normal fascicles. Neurofibromas typically have more involved fascicles than schwannomas,⁷¹ and schwannomas often have “onion skin” layers that can be gently dissected. Stimulation may be helpful in differentiating motor from sensory rootlets. Schwannomas typically arise from a sensory rootlet, and²⁰ in certain situations, especially in thoracic locations, sacrificing a rootlet may be necessary.

For tumors at the conus and cauda equina level, identification of the filum terminale will help to distinguish a nerve sheath tumor from a myxopapillary ependymoma. The filum typically is whiter than the nerve roots, it is surrounded by a squiggly vessel and intraoperative electrical stimulation will be negative.⁷² The filum should be divided cephalad first to avoid a retraction of the tumor into the conus.⁷² Spillage of tumor cells into the CSF should be minimized. Closure and completion of the operation are discussed above.

Complications of Surgery

Neurological Deficit

The most feared and devastating complication is that of a postoperative neurological deficit. In many cases, the cause remains allusive; however, the potential causes will be discussed with emphasis on complication avoidance.

Positioning is a particularly important part of the operation as it determines and facilitates the ease and safety of surgery. Patients with cord compression may be exquisitely sensitive to changes in position due to the resultant change in canal diameter. This may be assessed preoperatively when the patient is awake by testing the patient's range of motion to the point where symptoms appear. In patients with cervical tumors who have symptoms on minimal extension or the presence of L'Hermitte's sign, an awake fiber optic intubation should be strongly considered and extension avoided during positioning. Furthermore, the use of neurophysiological monitoring during positioning may be helpful. Care should be taken during the laminectomy to minimize pressure on the cord within a stenotic canal. The bone scalpel is an option for performing the laminectomy as it has been shown to reduce downward pressure.⁷³ The liberal use of magnification and microsurgical techniques are recommended during tumor resection. Respecting the tumor–pial interface and preserving pial vasculature is of paramount importance. In an unfortunate situation in which a patient awakes with an unexpected new neurological deficit, it is important to exclude reversible causes, such as a compressive hematoma or misplaced hardware. Urgent imaging is therefore recommended. In some cases, a deficit may be due to postoperative swelling but this is a diagnosis of exclusion.

Instability

Postoperative instability may occur in up to 10% of cases.⁷³ This is usually related to the extent of bony resection. In certain cases, where a facetectomy or wide exposure is required, particularly in the case of peripheral nerve sheath tumor consideration for segmental instrumentation should be given. There are increasing reports of minimally invasive spine techniques being employed for intradural tumor resection,^{74–77} including endoscopic techniques particularly in pediatrics.⁷⁸

CSF Leak

Despite watertight closure of the dura, CSF will invariably leak into the paraspinal region for a period of time.

Generally, this is not clinically apparent; however, complications may present themselves if there is persistent or cutaneous leak. Regular wound checks are performed to detect a cutaneous leak of CSF and if found should be addressed early to prevent infection. A contained pseudo-meningocele will generally regress without intervention but in rare situations a pseudomeningocele can cause compressive neuropathy.⁷⁹

Patients may present with low-pressure symptoms such as headache upon head elevation associated with nausea and vomiting. This is minimized with slow and gradual elevation of the patient after recumbency and returning to a supine position should symptoms emerge.⁸⁰ Patients with persistent symptoms, particularly if elderly, should have a CT brain scan to exclude intracranial pathology such as subdural collections or remote cerebellar hemorrhage, a recognized sequel of CSF leak.⁸¹

An identified leak can be confirmed to contain CSF using the laboratory test of beta 2 transferrin, which is unique to CSF and vitreous of the eye.⁸² Causative factors, such as raised CSF pressure or hydrocephalus, need to be excluded or treated. Other more common causes of wound drainage such as primary wound problems or infection can then be addressed. Revising the wound closure may be all that is required in association with resumption of recumbency. Cerebrospinal fluid diversion using a lumbar drain is often useful to facilitate wound healing; however, these are not without their own complications.⁸³ Other options include a blood patch⁸⁴ or the use of fibrin glue over the dura, although these are of limited benefit.

Pain

Patients may develop new pain or have worsening neuropathic pain postoperatively. In addition, patients will have expected postoperative wound pain. Individualized pain management by a pain team optimizing medical and other therapies is useful in minimizing this.

Outcomes

The best predictor of outcome is the patient's preoperative neurological status. However, tumor histology, grade, and extent of resection are also important predictors of outcome.^{8,85}

For meningiomas, a younger age of presentation has been associated with a more aggressive histology.⁸⁶ Myxopapillary ependymoma recurrence has been associated

with extent of resection.⁸⁷ The location of the tumor influences the extent of resection with conus tumors less likely amenable to gross total resection.^{18,87} Distant metastasis is rare but has been reported,⁸⁸ and tumor spillage into the CSF should therefore be minimized during resection.

For intramedullary tumors, gross total resection is much more likely in ependymomas and hemangioblastomas compared with astrocytomas.⁸⁵ Patients with incomplete astrocytoma resection need close follow-up with imaging, and radiotherapy should be considered for enlarging tumors.⁸ Higher-grade gliomas will require prompt neurooncology consultation for consideration of adjuvant treatment upfront. Patients with ependymoma recurrence should be considered for second resection.⁸⁵

CONCLUSION

Intradural tumors are rare and most are benign. They are distinguished by their location, with two thirds being extramedullary and one-third intramedullary. Surgery is indicated for symptomatic lesions, cases of diagnostic ambiguity, or radiological evidence of growth. Most lesions are surgically resectable except astrocytomas, which are often diffuse and poorly demarcated, and lesions of the conus where gross total resection may not be feasible.

KEY POINTS

- Intradural tumors are rare.
- Most tumors are benign.
- Two thirds are extramedullary and one third intramedullary in location.
- Surgery is the primary mode of treatment and indicated for lesions that are symptomatic, show radiological evidence of growth or where there is diagnostic ambiguity.
- Astrocytomas are often poorly demarcated and may be not amenable to complete resection.

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Spinal Intradural Vascular Malformations

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Snapshot

- » Anatomy
- » Classification of Spinal Arteriovenous Malformations
- » Summary of Epidemiological and Clinical Features
- » Diagnosis
- » Treatment
- » Complications
- » Other Treatments

INTRODUCTION

Spinal vascular malformations are uncommon pathologies, including both extra- and intradural lesions.¹ The clinical picture and evolution depend on the underlying pathophysiologic mechanism: hemorrhage, spinal cord ischemia secondary to either a phenomenon of spinal cord blood flow steal or to venous congestion or thrombosis, or mass effect.^{2,3} Extradural malformations, which are the most common ones and representing >80% of all lesions, include vertebral hemangiomas and intraspinal-extradural vascular malformations.⁴ The intradural lesions include intramedullary glomus arteriovenous malformations (AVMs), juvenile AVMs, spinal dural arteriovenous fistulas (SDAVFs), spinal cord (intradural perimedullary) arteriovenous fistulas (SCAVFs), and cavernous malformations (CMs).⁵⁻¹⁰

ANATOMY

The vascular network supplying the spinal cord is formed by vertebromedullary arteries, which originate from vertebral arteries in the cervical segment and from intercostal and lumbar arteries in the lower segments of the spine. Each vertebromedullary artery enters the spinal canal through a vertebral foramen together with a spinal nerve and divides into a vertebral branch and a medullary (or spinal) branch. This penetrates the outer dural layer and

is then divided into a dural artery and a radicular artery. The dural artery provides blood supply to the spinal and nerve root dura. Anterior and posterior radicular arteries, which originate by the bifurcation of the radicular artery, provide the vascularization of anterior and posterior nerve roots. Moreover, the anterior radicular artery passes above the ventral surface of the spinal cord, where it connects to the contralateral one in the midline and forms the anterior anastomotic artery, also named anterior spinal artery (ASA). Each posterior radicular artery on the posterolateral surface of the spinal cord is divided in an ascending and a descending branches, forming on both sides the posterolateral anastomotic vessels or posterior spinal arteries. The ASA and the two posterior spinal arteries are linked by a dense network of subpial anastomotic branches, forming the so-called perimedullary arteries network. Several perforating arterial branches, which are further distinguished in long branches supplying the grey matter and short ones supplying the white matter, originate from this vascular structure.¹¹⁻¹⁵

The blood supply to the mid-thoracic and inferior segments of the spinal cord (Th8-L2) and cauda equina is provided by the great anterior segmental medullary artery, also named with the eponym of Adamkiewicz artery. In 75% of people, this artery originates on the left side of the aorta between the T8 and L1 vertebral segments,^{16,17} and gives anastomotic branches to anterior and posterior spinal arteries.

A complex network of veins surrounding the spinal cord forms a venous coronal plexus as well as usually paired longitudinal veins. The radicular vein segmentally receives blood from this network, then pierces the dura in close proximity of the radicular axilla.¹⁸ A good correspondence between arterial anatomical distribution of arteries and venous anatomy can be found in children. Indeed, a larger anterior median vein and two paired dorsolateral veins are recognizable on the surfaces of spinal cord. Additionally, a posterior median longitudinal venous collector can also be present. Conversely, in adults the presence of anastomotic branches may vary, and the ectasia or tortuosity of existing vascular tracts makes the interpretation of anatomy complicated. Cadaveric anatomic observation revealed that functional valve-like structures may be present between the epidural draining system and the intradural venous complex in order to minimize the reflux of blood from the epidural space.¹⁹

Interestingly, it is remarkable that the above-described dural artery and the corresponding vein can give rise to an arteriovenous shunt within the dura, in close proximity to the origin of the spinal root.

CLASSIFICATION OF SPINAL ARTERIOVENOUS MALFORMATIONS

Over the years, different classifications of spinal AVMs have been proposed.²⁰⁻²³ These were based on intraoperative pathological appearance before the clinical introduction of spinal angiography²⁴ or on more detailed arterial and venous blood flow patterns demonstrated by spinal angiography.²⁵⁻²⁷

Classically, four AVM types are recognized: type I, dural arteriovenous fistulas (AVFs); type II, intramedullary glomus AVMs; type III, juvenile AVMs; and type IV, intradural, direct AV fistula. A type V malformation, consisting in an extradurally sited type III AVM, with peculiar pathoanatomical features, was subsequently added by Morgan and Morrill.²⁸

In 1987, Rosenblum et al. reviewed their own clinical data and proposed to differentiate spinal AVMs into malformations and fistulas, with either an intradural or dural location. In this up-to-date classification, intradural malformations included intramedullary glomus and juvenile AVMs as well as extramedullary AVFs. Dural malformations, specifically AVFs, were defined as having a retrograde drainage into perimedullary veins.²⁹

Spinal AVFs were found to have different and peculiar venous patterns, and such diversity was considered to be an important factor to evaluate in treatment decision-making process. In 1995 Borden et al. proposed a three-type classification of dural AVFs: type I, with an anterograde drainage into the epidural veins; type II, with a venous drainage into epidural (anterograde) and perimedullary (retrograde) drainage; and type III, with only a retrograde, i.e. perimedullary, venous drainage.³⁰ Two years later, in 1997 Bao and Ling also proposed some classification changes based on their experience in a series of patients.³¹ Their proposal for intradural AVFs defined three types of AVFs according to the number of feeding vessels and intensity of blood flow. In 1998, Kikuchi and Myasaka, considered three types of spinal vascular malformations: dural AVF, perimedullary AVF and intramedullary AVM.³² Perimedullary AVFs were further subcategorized into types 1-3 depending on the size of vascular pedicles.

In 2002 Rodesch et al. published their classification of spinal cord arteriovenous shunts: a distinction between AVMs and AVFs was presented, with the latter classified as either micro- or macrofistulas.³³ Furthermore, they identified (1) genetic hereditary lesions (macrofistulas and hereditary hemorrhagic telangiectasia), (2) genetic non-hereditary lesions, and (3) single lesions.

In the same year, Spetzler et al.⁸ proposed a new classification, as did Zozulya et al.⁹ in 2006.

Spetzler et al. identified a broad variety of vascular malformations, which were divided into three primary categories: neoplasms, aneurysms, and arteriovenous lesions. Neoplastic vascular lesions include CMs and hemangioblastomas, which both occur sporadically and familiarly; the second category includes the rare spinal aneurysms, which can arise from either radicular or main arteries, i.e. artery of Adamkiewicz; the third category is divided into AVMs and AVFs. In particular, AVFs are subdivided into extra- and intradural ones, with the latter categorized into ventral or dorsal lesions. Ventral AVFs can present small (type A), medium (type B) or large (type C) shunt; dorsal AVFs can have single (type A) or multiple (type B) feeders. The AVMs are divided into extradural-intradural and intradural malformations according to their neuroanatomical features. Intradural AVMs are further divided into intramedullary, intramedullary extramedullary and conus medullaris malformation. This is a newly classified juvenile-type AVM located in the conus medullaris and showing a better prognosis following surgical treatment. The Spetzler's classification proposal aimed at eliminating

the confusion inherent in previous classifications and, most importantly, at determining the appropriate surgical treatment.

Nonetheless, 4 years later Zozulya et al. designed a novel classification based on the anatomical characteristics and angiostructural and hemodynamic features. Zozulya argued that classification proposed by Spetzler was incomplete, not covering the entire spectrum of spinal malformation types. Zozulya's classification considered three parameters to define vascular malformations: localization (axial and lengthwise), vascular structure (feeding vessels, structural features, and venous drainage), and hemodynamic features. Axial localization is related to anatomical relationship between the lesion and the spinal cord, instead lengthwise depends on vertebral level. According to axial localization, malformations were divided in intramedullary, perimedullary, dural, epidural or combined. The structure of vascular malformations represents for importance the second parameter to be considered. According to this feature, AVM and AVF can have compact or diffuse arrangement of the nidus vessels. Taking into account hemodynamic data, the authors described three different types of blood flow (low, type A; moderate, type B; high, type C). To simplify the classification, the authors suggest to indicate first the axial localization of the malformation and its structural peculiarities, and then the other features (vertebral level, hemodynamic characteristic) as supplementary data. This new classification, in the authors' opinion, should be helpful to direct the decision process for best therapeutic strategy. Indeed the treatment—endovascular, microsurgical or combined—strictly depends on the type of malformation.

In the same year of Zozulya's paper, Kim and Spetzler published a new updated classification of spinal vascular malformation, based on anatomy and pathophysiology.¹⁰ First, the authors distinguished spinal arteriovenous lesions in arteriovenous fistulae and AVMs. These lesions were classified as extradural, extra-intradural or intradural. Intradural lesions were further divided into ventral or dorsal fistulae or into intramedullary lesions. The latter ones were defined as compact or diffuse. A new category, conus medullaris AVMs, was described as a new distinct entity.

In 2009 Da Costa et al. reported a 20-year experience on the surgical management of spinal vascular lesions, focusing on the correlation between classification and management.³⁴ He introduced a classification based on physiological and genetic data, according to which these lesions were considered as expression of a complex disease partly congenital and partly acquired.

Recently, Qureshi proposed a new classification scheme for spinal vascular malformations, based on angiographic data.³⁵ The most interesting aspect of his proposal is the statistical analysis performed to determine the inter-observer reliability of the new classification. He concluded that his new scheme proved to be sufficiently reliable even if used by less expert hands.

Such an increasing, and evolving, number and types of classification of spinal vascular malformations are testimony of the lack of a definitive and satisfactory patho-anatomical and physiological classification useful to help in deciding the best treatment modality in each single patient.

SUMMARY OF EPIDEMIOLOGICAL AND CLINICAL FEATURES

Regardless of the above described classifications, the epidemiological and clinical data related to the major spinal intradural vascular lesions are summarized.

Spinal vascular malformations are often underdiagnosed³⁶ and occur more frequently in male (male: female ratio of 2:1 to 4:1)³⁷ between 30 and 70 years of age. The thoracolumbar levels are the most frequently involved.^{2,38} The bleeding rate is related to the type of the vascular lesion. However, it should be highlighted that currently available epidemiological data are still partial and not completely reliable, because of lack of prospective studies on large cohort of patients.

Spinal Dural Arteriovenous Fistulas

Spinal dural arteriovenous fistula (SDAVF) is an arteriovenous abnormal communication that occurs within the dura of the spinal cord with the arterial supply usually arising from a dural branch of radicular artery.³⁹ An intradural vein drains the shunt directly into the pial veins of the cord leading to venous engorgement and venous hypertension, which in turn may lead to a venous hypertensive myelopathy. The chronic effects are believed to result in a myelopathic syndrome identical to that described by Foix and Alajouanine in 1926.⁴⁰ SDAVs represent the most frequent (70%) spinal vascular malformation and are believed to be an acquired condition resulting from thrombosis of the extradural venous plexus.^{36,41-43} They are usually tiny lesions, most commonly seen between Th5 and L3, and located adjacent to the intervertebral foramen.

The most common clinical presentation is related to myelopathy, with subacute or chronic onset of symptoms.⁴⁴ Hemorrhage is uncommon in SDAVs, which typically

appear in middle age causing a progressive worsening of neurological status. The clinical onset is characterized by pain, weakness, abnormal gait, urinary, and/or sphincteric disturbances.

Spinal Cord (Intradural or Perimedullary) Arteriovenous Fistulas

Spinal cord (intradural or perimedullary) arteriovenous fistulas (SCAVFs) consist of AVFs located on the surface of the spinal cord and fed directly by arteries supplying the cord, most frequently the ASA.⁴⁵ In dural location of the shunt, constant involvement of arteries supplying the spinal cord and lack of intervening nidus are angioarchitectural features that differentiate SCAVF from both SDAVF and SCAVM.^{46,47} They represent about 8–19% of all spinal intradural vascular malformation and are considered congenital lesions. Patients usually present in their second-to-fourth decade and the most common neurologic presentation is characterized by progressive asymmetrical radiculomedullary signs involving the lower extremities, related to the location in the lower thoracic, and lumbar region. Hemorrhage is also common.

Spinal Cord Arteriovenous Malformations and Subtypes

Spinal cord AVMs are believed to be congenital lesions. Most patients present in their second through fourth decade. The nidus of the AVM is located on or within the parenchyma of the spinal cord itself with arterial supply from anterior and posterior spinal artery or their branches. A feeding artery aneurysm is common due to the high flow nature of spinal AVMs. Intradural spinal AVMs comprise approximately 10–15% of all spinal AVMs.^{8–10,48} The incidence of subtypes is not totally clear because of the rarity of these lesions. The glomus subtype is characterized by a relatively compact nidus. The much less common juvenile subtype, also known as diffuse AVM, is characterized by an exceptional extension, with additional extramedullary and often extraspinal extension. The presence of AVM, especially type II and III (true AVMs), can determine stealing of blood from normal neural tissue leading to ischemia, venous hypertension, thrombosis and, most often, hemorrhage. This means that acute onset of symptoms is typical in case of hemorrhage; conversely, a progressive myelopathy could occur in case of blood steal and venous congestion (younger patients).⁴⁹ Spinal AVMs are most

common in the cervical and thoracolumbar region but may be found at any spinal level, including the filum terminale.

Spinal Cavernous Malformations

Unlike AVMs and AVFs, CMs are vascular lesions without high-flow AV shunts. Histology is similar, if not identical, to their counterparts in the brain. The CMs are intramedullary lesions and could affect the whole spinal cord.⁵⁰ Cauda equina and filum terminalis can also be involved.^{51,52} Typically, natural history of CMs is characterized by episodes of subclinical or not dramatic hemorrhage, alternating with long-time stability of the lesion. Patients most commonly present with discrete episodic neurologic dysfunction, with variable recovery between episodes. Monophasic acute or chronic deterioration of spinal cord function may also occur. The acute symptomatology is probably secondary to hemorrhage.

Spinal Aneurysms

Isolated spinal aneurysms are a very rare condition.⁵³ They are usually associated with other vascular lesion as AVM. Only few cases of isolated spinal aneurysms are reported and the treatment is usually endovascular.^{54,55} Patients may experience a spinal cord stroke or a subarachnoid hemorrhage. Aneurysms can occur within the arterial supply or venous outflow connections of the spinal cord. They are usually identified by their location, i.e. radicular artery aneurysm. There is not a clear predilection site at any specific segment of the spinal arteries. They are usually fusiforme and related to other general pathologies.⁵⁶ Differently from the intracranial aneurysm, spinal aneurysms are commonly expression of a systemic disease. Some cases of spinal aneurysm related to mycosis, vasculitis, hematologyphopietic or immune diseases have been described.^{56–58}

■ DIAGNOSIS

Diagnosis of spinal vascular malformations represented for many years the main challenge in the management of these conditions. The evolution of understanding and classification of these lesions is historically linked with their definition and presurgical recognition. Undoubtedly, the introduction of selective and ultrasensitive spinal arteriography in the 1960s, the subsequent widespread diffusion of magnetic resonance imaging (MRI) in the

1980s–1990s and, finally, the refinement and implementation of these radiological techniques allowed to improve the knowledge of anatomy and pathophysiology of spinal vascular lesions. Moreover, in the last decades, the large use of operative microscope [integrated in the last years with a device for intraoperative indocyanine green (ICG) videoangiography during neurosurgical procedures and the improvement of operative techniques allowed not only a postoperative good functional recovery but also a better knowledge of anatomy, pathophysiology and hemodynamic of spinal vascular lesions.⁵⁹

In cases of chronic or subacute onset of symptoms, the distribution of pain is not a reliable method to identify the site of the lesion. A clinical picture characterized by sensory involvement is generally related to a posterior localization; conversely, the anterior position of the lesion determines a upper or lower motor disorders, with or without pyramidal signs, that usually occur in the late stage of the disease.³⁷ The physical examination can orientate the diagnosis if two peculiar signs are detected: an arterial murmur (“the spinal bruit”)⁶⁰ that can be heard by placing a stethoscope over the spine is considered diagnostic for “true” AVMs (type II and III); the second sign to search is the presence of a cutaneous angioma on the back that could indicate the level of the malformation.²⁶

Neuroradiological diagnosis is the last and the most important step in pretreatment stage. The gold standard examination for the morphological definition of spinal vascular lesions still remains spinal angiography, except in cases of CMs.^{61,62} Angiography allows to exactly locate the lesion, depicting its extent, and investigating its angioarchitecture. Spinal angiography is indeed a dynamic examination that is able to show feeding pedicles and draining vessels, flow-related aneurysms and a nidus in case of AVMs. Stenosis of feeding and draining vessels should be also addressed for a correct treatment plan. The main limitations of spinal angiography are related to the difficulty in definition of precise arterial feeders in cases of extensive juvenile malformations with dilated arterialized veins involving multiple spinal levels. It is important to highlight that not every angiography exam can distinguish the precise location of the vascular lesion in respect to spinal cord (i.e. peri- or intramedullary localization).⁶³

Magnetic resonance imaging and computed tomographic (CT) scan angiography are of diagnostic value as well. In particular, MRI demonstrates dilated as well as thrombosed vessels, venous congestive myelopathy and intra- or perimedullary blood. Moreover, it allows a differential diagnosis between cavernomas, other vascular

lesions, intramedullary tumors and other spinal cord lesions such as axonal demyelination or infarction.⁶⁴ The MR typical features suggesting the presence of a fistula include: intramedullary hypointensity and flow voids on the cord surface (in T1 weighted sequences) prominent serpiginous intradural extramedullary flow voids along the dorsal aspect of the spinal cord, usually spanning more than three segments (in T2 weighted sequences, Figs. 121.1A and B, 121.2A, and 121.5B).

If angiography still plays an essential role in diagnosis of “true” AVMs (type II and III), last-generation MRI scan (Figs. 121.1C and D and 121.2B to D) and angio-CT scans (Fig. 121.1E) with multiplanar reconstruction have gained popularity in the recent years, as reliable, safe, and less invasive alternative in diagnosis of AVFs.^{65,66}

Currently, the armamentarium of neuroradiologists should be considered as an integration of different tools, including angiography, MRI, and CT. In the preoperative management of these complex pathologies, it is essential to acquire data from all imaging modalities, when applicable, in order to define the anatomy, the hemodynamic and the relationship with the spinal cord of these vascular lesions.

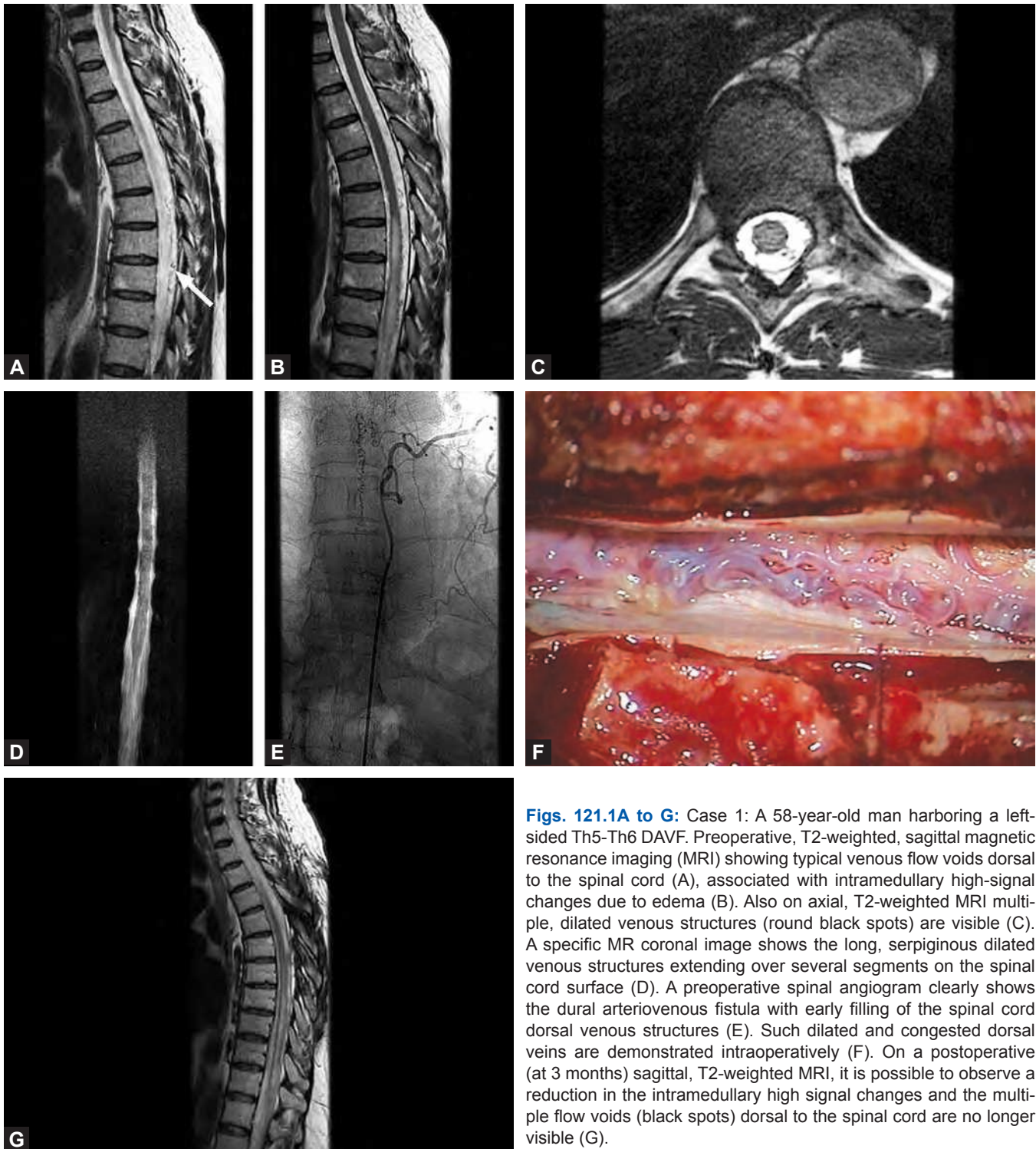
TREATMENT

Current opinions regarding the management of ruptured AVMs suggest a multimodal approach based on a combination of different therapies, including nonsurgical ones.^{67,68} In the contemporary “endovascular era,” surgery plays an increasingly limited but still crucial role. Indeed, surgical treatment of ruptured AVMs remains the only therapeutic modality in selected cases. Despite vascular neurosurgery has been recently deprived of the significant role typically retained in the past decades, as primary treatment modality, technological innovations like the use of intraoperative videoangiography^{69,70} and neuromonitoring⁷¹ have introduced a very useful support in the surgical management of vascular malformations.

Preoperative neurophysiologic evaluation by somatosensory evoked potentials (SSEPs) and motor evoked potentials (MEPs) is useful to assess spinal cord function, according to the pattern of vascularization and location of the lesion.

Surgical Treatment

The goal of surgical treatment of intradural vascular malformations is the resection and/or the exclusion of the



Figs. 121.1A to G: Case 1: A 58-year-old man harboring a left-sided Th5-Th6 DAVF. Preoperative, T2-weighted, sagittal magnetic resonance imaging (MRI) showing typical venous flow voids dorsal to the spinal cord (A), associated with intramedullary high-signal changes due to edema (B). Also on axial, T2-weighted MRI multiple, dilated venous structures (round black spots) are visible (C). A specific MR coronal image shows the long, serpiginous dilated venous structures extending over several segments on the spinal cord surface (D). A preoperative spinal angiogram clearly shows the dural arteriovenous fistula with early filling of the spinal cord dorsal venous structures (E). Such dilated and congested dorsal veins are demonstrated intraoperatively (F). On a postoperative (at 3 months) sagittal, T2-weighted MRI, it is possible to observe a reduction in the intramedullary high signal changes and the multiple flow voids (black spots) dorsal to the spinal cord are no longer visible (G).

lesion from the normal vascular network, respecting the normal blood supply without damaging the spinal cord. Obviously, the surgical technique depends on the type of lesion.

Spinal Dural Arteriovenous Fistulas

The surgical treatment of SDAVFs still remains the gold standard procedure. Indeed, endovascular treatment does

have limitations due to the lack of long-term effectiveness of the occlusion. The aim of surgery is the interruption of communication between the arterialized vein piercing the dura and the congested coronal plexus. If this vessel is not recognizable, a correct interruption of the shunt is obtainable resecting the intradural nidus. Historically, the nidus of SDAVFs was wrongly identified in the large, tortuous, and congested pial venous plexus. This misunderstanding guided many surgeons' strategy to excise the coronal plexus by stripping off vein(s) from the spinal cord. This challenging procedure was always responsible for real disasters, without even being able to interrupt the abnormal communication in many cases.⁷²⁻⁷⁵ The dissected and removed congested plexus was instead the spinal cord normal venous drainage, with a retrograde flow. Therefore, the excision of such coronal plexus led to a further increase in venous congestion. Fortunately, a deeper knowledge of spinal cord's hemodynamics as well as of pathophysiology of SDAVFs allowed a change in anatomic target.

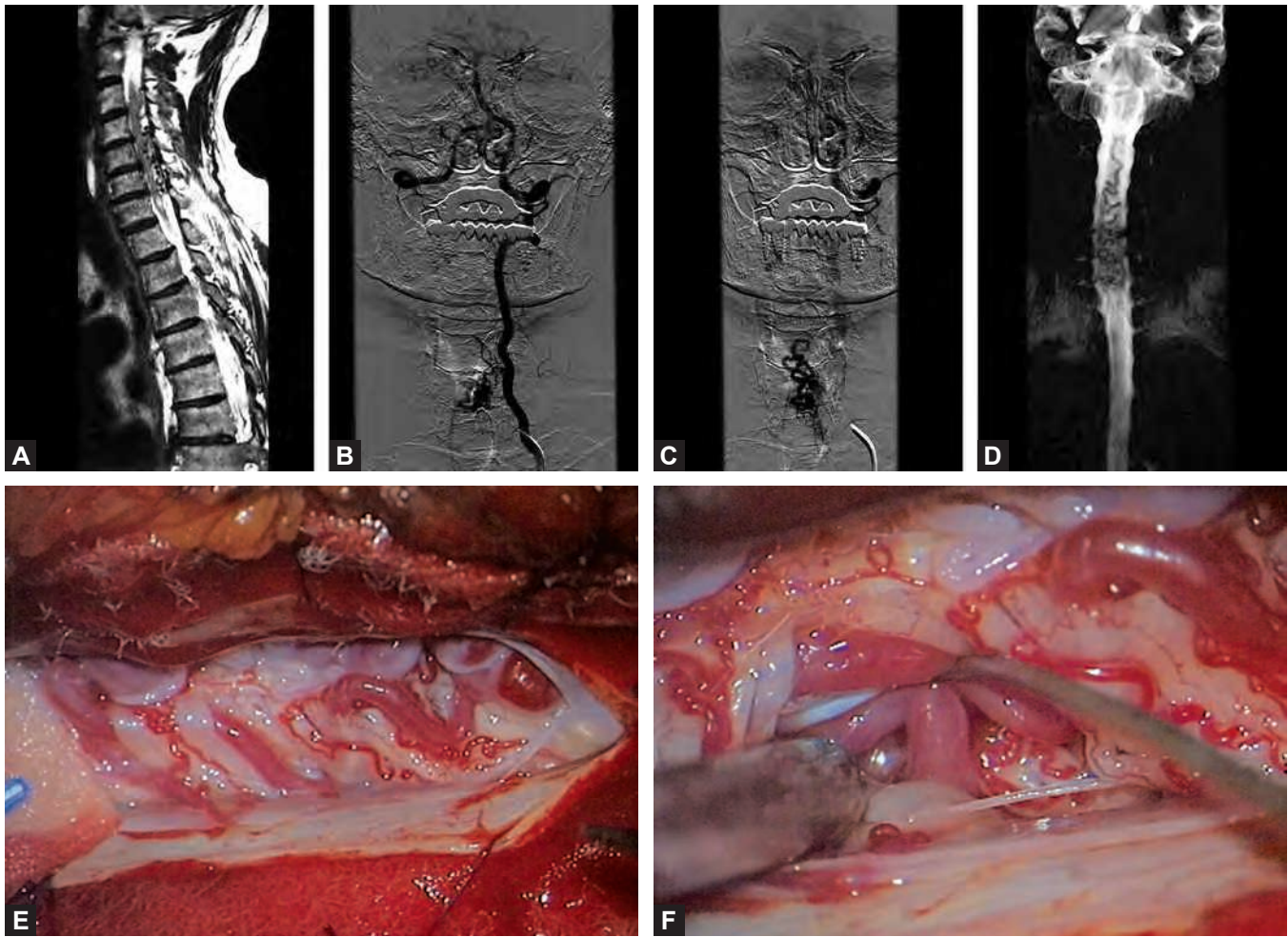
Surgery can be performed with a uni- or bilateral laminectomy extending one level above and one level below the nidus and the arterialized vein piercing the dura. After dural opening and exposing the spinal cord with dilated pial venous plexus, the fistulous point and feeder artery should be visualized (Fig. 121.1F). Such identification could be complex. The correct identification of the abnormal vessel could be obtained by accurate study of preoperative angiogram, remembering that the arterialized vein pierces the dura at level of posterior nerve root. However, the recent introduction of intraoperative ICG videoangiography allowed a faster and safer management of such surgical step. After individuation of the arterialized vessel, this is coagulated with bipolar forceps in a short segment (about 5 mm) near the dura. It is also described the placement of one or two vascular clips before coagulation. Controversy still exists about the need to complete the interruption by cutting the vessel.⁷⁶ Moreover, the ICG videoangiography helps to verify the correct and complete interruption of the shunt.^{69,70,77} Indeed, after coagulation or clipping of feeder vessel, the dilated venous plexus usually loses the usual "turgor" and it is possible to detect a change from reddish to bluish in the veins' color. The ICG videoangiography further confirms this observation, showing the restoration of normal blood flow direction and velocity. This will be slower and will have an opposite direction compared to preinterruption ICG videoangiography control.

Spinal Cord (Intradural) Arteriovenous Fistulas

As already mentioned for SDAVFs, the goal of surgical treatment of SCAVFs is the interruption of abnormal vessel causing the shunt between arterial and venous networks. This chapter discusses only intradural vascular malformation, and extramedullary fistulas will not be covered here. These lesions were classified by Merland in three different groups:⁴² small fistula located in the conus or filum terminale furnished by an abnormal ASA that appears long and thin (type I); a large fistula located anterolaterally or posterolaterally on the spinal cord surface with a lot of feeders from anterior or posterior spinal arteries (type II); a single giant fistula fed by abnormal ecstatic anterior and posterior spinal arteries (type III). Surgical treatment for type II lesion may be definitive, despite anterior or lateral location could make difficult the approach. A transvertebral route or a posterolateral approach with rotation of spinal cord could be performed with satisfactory results (Fig. 121.1G).^{27,78-80} For type I lesions with a lot of feeders, embolization may be performed before surgery in order to reduce vascular supply. Similarly a multimodal and multistep treatment, combining surgery and endovascular procedures, can be the best way to manage complex type III fistulas. In these cases, the goal of treatment is to halt the progression of myelopathy in order to improve the outcome.

Spinal Cord Arteriovenous Malformations and Subtypes

It does not exist the "best way" to manage spinal AVMs. The treatment is often a compromise between different therapeutic strategies. The decision for an adequate therapeutic planning should be individualized, taking into account the patient's health conditions, neurological status and, above all, the characteristics of the malformation. Many concerns are related to the timing of surgery in case of ruptured AVMs.^{47,48} The current trend is to delay the treatment in order to allow clot lysis and absorption of blood. However, surgical treatment of spinal AVMs is a real challenge for the neurosurgeon, who should apply every technological and human resource with the aim to minimize the risks and improve the outcome. As already discussed about SDAVFs, surgical exposure should be extended at least one level above and one level below the nidus (Figs. 121.2E and F). It is crucial a correct preoperative planning in order to accurately identify the exact



Figs. 121.2A to F: Case 2: A 66-year-old man suffering from spinal cord arteriovenous malformation. Preoperative, sagittal, T2-weighted magnetic resonance imaging showing many flow voids dorsal to the spinal cord; high signal changes are also seen inside the cord itself (A). A spinal angiogram shows, both in the arterial and in the venous phases, the arteriovenous malformation (B and C). A coronal, MR reconstruction clearly demonstrates the cervicothoracic vascular malformation (D). Intraoperative pictures (E and F) show a tangle of arteries and veins circumferentially located on the surface of the spinal cord, with some branches also entering the spinal cord's surface.

location of the nidus respect to vertebral bodies. The dura should be incised in the midline and a sharp dissection is preferable in order to avoid arachnoid injury. This can lead to laceration of adherent vessels under the dura. At the opening and exposure step, a very accurate hemostasis using bipolar forceps is recommended because the bleeding could stain surgical field, making difficult the recognition of the angioarchitecture of the nidus. After a good exposure, obtainable in case of intramedullary AVMs by a median sharp myelotomy, the interpretation of the anatomical features of AVMs is the most important phase before starting with coagulation and excision. Certainly, an accurate comparison with preoperative imaging is useful, but the application of

technologies could make the difference in complex cases. Intraoperative ultrasonography with the application of microprobes has a great usefulness to distinguish afferent from efferent branches. Additionally, hemodynamic data should be integrated by the application of intraoperative ICG videoangiography.⁸¹ This tool demonstrated a good effectiveness in not only depicting the anatomy of AVM nidus, but also giving real-time information about blood flow to the nidus vessels from it. When surgeon will have made all necessary reasoning about the AVM, the dissection may start. It is crucial to be sure to coagulate afferent branches in order to reduce first blood supply to the nidus and turgor of abnormal vessels. This reduces the risk of intraoperative bleeding and allows a better manipulation of

the lesion itself. Care should be taken in order to avoid the coagulation of an efferent vessel. This can lead to a dramatic increase of blood pressure into the nidus with a great risk of intraoperative rupture of AVM. In the dissection phase, bipolar forceps should be used electively on vessels, in order to avoid thermal damage on the spinal cord. Continuous irrigation is recommendable to maintain clean the surgical field and avoid sticking between forceps and vessels. For the largest feeders, ligatures or vascular clips could be applied. If ICG videoangiography is available, a last check after resection of the nidus is advisable. In cases of giant AVMs, multimodal treatment is advocated. In these cases, preoperative embolization can reduce the blood supply and may help the identification of feeders because particulate materials used for occlusion settle into afferent branches more than into efferent ones. Totally intramedullary AVMs should be considered for surgery only in selected cases. Ventral localization and great longitudinal extension are considered indication for repeated endovascular occlusion treatments. Giant juvenile type should be reasonably considered inoperable.

Spinal Cord Cavernous Malformations (Figs. 121.3A to G)

General considerations for indication to surgery in cases of spinal cord CM are the same already mentioned for AVMs. The ideal condition for surgery is a CM localized in the posterior half of the spinal cord, and accessible through the midline. Surgery for CM is similar to surgery for benign intramedullary spinal cord tumors (Figs. 121.3C and D). The goal of this surgery is the complete resection of the malformation because the residual nidus of angiomas tends to rehemorrhage, causing recurrent myelopathy. For this reason, an accurate inspection of the surgical bed of the malformation is advisable. Moreover, the presence of a hematoma in cases presenting with hemorrhage may complicate the procedure; therefore, a complete evacuation of the blood is mandatory before nidus resection.^{82,83} The potential usefulness of application of ICG videoangiography in spinal CM is controversial.⁸⁴ Probably, a large series of patients treated with this tool is required to draw meaningful conclusions about the pattern of fluorescence of such malformations.

Spinal Aneurysm

Because of their extreme rarity, isolated spinal aneurysms do not have a precise definition for management and

treatment. Usually, in unruptured cases related to systemic diseases, the first step consists in the management of the underlying pathology. Generally, surgical treatment of any spinal aneurysm should be performed only if the various types of inflammatory and noninflammatory vasculopathies are excluded as possible underlying etiology. Because many of the reported spinal aneurysms have a fusiform rather than saccular shape, standard surgical treatment may consist in trapping of the aneurysm or wrapping.⁵⁶

Endovascular Treatment

Goal and Indications

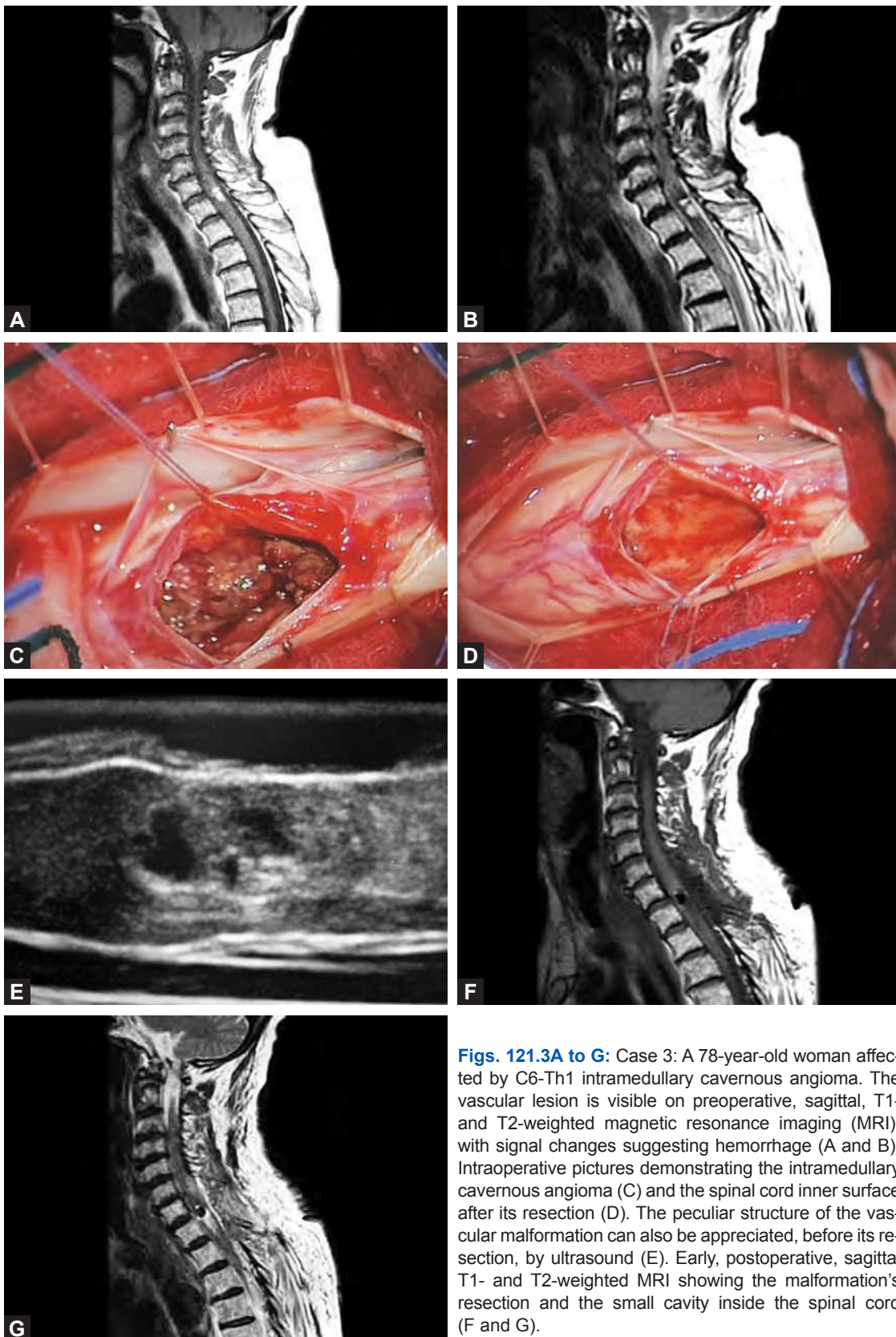
The goal of endovascular treatment of spinal vascular malformations is obliteration of the arteriovenous shunt with preservation of arterial supply and venous drainage of the spinal cord. It is crucial to occlude the AV shunt as distally as possible in order to reduce the risk of collateral recanalization. Symptomatic lesions should be treated as early as possible because the best predictor of clinical outcome is the pretreatment functional status.⁸⁵

Over the last decades, endovascular techniques are gaining appeal for the less invasiveness of the procedure over other therapeutic options; they allow diagnosis and treatment during the same session, even though in some cases multiple-step embolization is required.

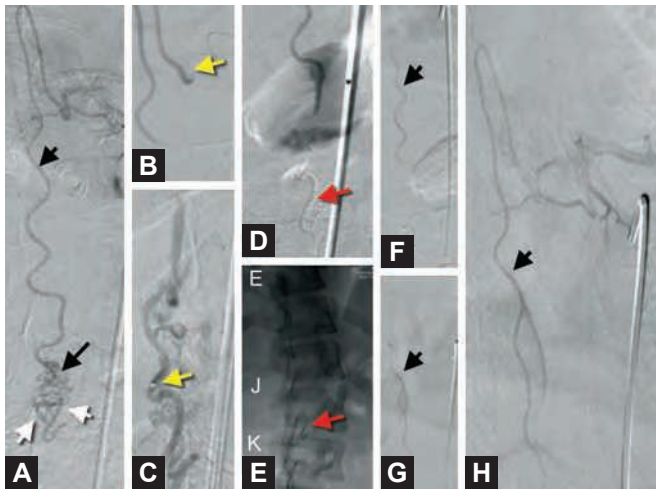
The main indications for endovascular procedures are the following:

Symptomatic Spinal Vascular Lesions:

- *Arteriovenous fistulas (AVFs)*:
 - *Intradural dorsal AVFs (type I)*: when the dural artery supplying the shunt does not stem from a radiculomedullary branch. In this latter case, embolization may result in inadvertent occlusion of the ASA; in the latter condition, surgery is the best treatment option.^{8,10,61}
 - *Intradural ventral AVFs (type IV)*: endovascular management is well described for all three subtypes, even in case of giant lesions (subtype C of Spetzler classification), which display complex angioarchitecture with multipedicled feeders.^{61,86-87} Superselective catheterization allows visualization of flow-related aneurysms on feeders arising generally from ASA, which is necessary to identify accurately and to preserve proximally as well as distally (Figs. 121.5A to E).

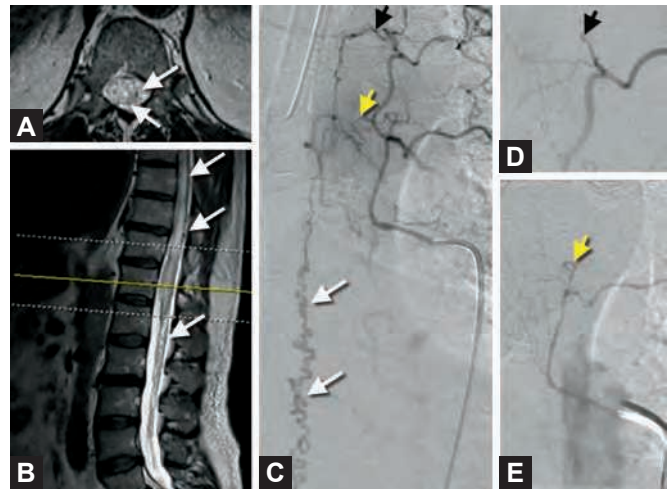


Figs. 121.3A to G: Case 3: A 78-year-old woman affected by C6-Th1 intramedullary cavernous angioma. The vascular lesion is visible on preoperative, sagittal, T1- and T2-weighted magnetic resonance imaging (MRI), with signal changes suggesting hemorrhage (A and B). Intraoperative pictures demonstrating the intramedullary cavernous angioma (C) and the spinal cord inner surface after its resection (D). The peculiar structure of the vascular malformation can also be appreciated, before its resection, by ultrasound (E). Early, postoperative, sagittal T1- and T2-weighted MRI showing the malformation's resection and the small cavity inside the spinal cord (F and G).



Figs. 121.4A to H: (A) Preoperative catheter angiogram of a 32-year-old man presented with progressive cauda-conus medullaris syndrome secondary to a perimedullary arteriovenous malformation (AVM) at the conus medullaris (black arrow). This AVM is supplied by the anterior spinal artery (ASA), arising from a left-sided artery of Adamkiewicz (black arrowhead), branch of the thoracic aorta at the level of the 9th thoracic vertebra and drained by extrinsic perimedullary veins located over the anterior surface of the spinal cord (white arrows). (B and C) Note the UltraFlow flow-directed microcatheter (eV3, Paris, France) (yellow arrow) advanced progressively into the ASA, as far distally as possible. (D) Injection of glue, a Glubran 2-Lipiodol mixture (GEM, Viareggio, Italy) (red arrow), inside the arterial branch supplying the AVM, without reflux inside the ASA. (E) Note the glue (red arrow), projecting at the level of L2-L3 disc space. (F and G) Post-embolization spasm of ASA (black arrowheads). (H) Postembolization angiogram shows the ASA spasm resolved by a selective intra-arterial injection of papaverine (black arrowhead) (Ainhoa, France). No residual AVM is seen.

- *Arteriovenous malformations (AVMs):*
 - *Extradural-intradural AVMs (type III; juvenile; metameric):* these lesions are difficult to cure and their treatment is often palliative, the realistic goal being the reduction of vascular steal and vein engorgement, in order to ameliorate or stabilize the patient's neurological picture.^{8,10,61,86,87}
 - *Intradural-intramedullary AVMs (type II, glomus):* although complete embolization of such AVMs has been reported,⁶² as well as radical surgical resection,⁸⁸ even partial obliteration can improve patient's prognosis.⁶² Surgery alone is rarely the procedure of choice, especially when the nidus is diffuse and there are multiple feeders. However, combined endovascular and microsurgical treatment may offer the best chances for control of neurological decline.^{61,88}



Figs. 121.5A to E: A 45-year-old man presenting with progressive paraparesis secondary to intramedullary edema in the lower thoracic and lumbosacral spinal cord seen as hyperintensity in axial (A) and sagittal (B) T2-weighted magnetic resonance imaging. Flow voids (white arrows) surround the thoracic spinal cord and conus and are consistent with venous hypertension. Yellow line on sagittal image (B) indicates the level of the axial slice. (C) Catheter angiogram showing a dural arteriovenous fistula (DAVF) supplied by left third (black arrowhead) and fourth (yellow arrowhead) intercostal radiculomeningeal arteries forming a network (white arrows). The DAVF drains into a radicular vein connected with congested perimedullary veins (white arrows). (D and E) Postembolization angiograms after injection of both intercostal arteries show no residual fistula.

- *Conus medullaris AVMs:* for these very complex lesions, treatment is rarely purely endovascular, especially when dilated venous channels indicate surgical decompression of nervous structures to relieve neurological symptoms (Figs. 121.4A to H). Careful identification of ASA and branches of posterior spinal arteries separated from the malformation is crucial for avoiding postoperative neurological compromise.^{61,88}

In all cases, feasible selective catheterization of the feeding pedicles and familiarity of the treating physician with the use of liquid polymerizing agents are prerequisites for a successful embolization.

The contraindications of these procedures are the same as a routine procedure for intradural DAVFs: it is not suggested endovascular treatment when arterial feeders arise from arteries supplying the spinal cord nor when a CM is suspected.

Expert Suggestions/Comments

A thorough search of the vascular malformation must be conducted at all spinal levels as well as in the sacral and

cranial vasculature. As a matter of fact, AVMs and AVFs may often present with venous congestion many spinal levels away from the symptomatic level because of the longitudinal orientation and valveless nature of the spinal veins.⁷⁶

It is paramount to master the use of various liquid embolic agents (LEAs) in order to take advantage of the properties of each, especially viscosity, which helps in controlling their deposition.^{61,88}

Adjusted-dose intravenous heparin is used by the authors for the treatment of venous thrombosis when it extends to spinal cord draining veins, complication readily visible on angiograms.

Finally, when one is not certain about the consequences that an injection of LEA may have, the functional importance of the targeted branch, the stability of the microcatheter or the possible reflux of the embolic agent, it is better not to embolize at all than taking the chance.

Key Steps of the Procedure

The patient is under general anesthesia, in order to ensure comfort to the patient and reduce motion artifacts inducing apnea at the beginning of each image run. A percutaneous transfemoral modified Seldinger technique is used to introduce the catheter into the aorta. The sheath is introduced first, then a 6 French catheter is introduced through it and placed in the common femoral artery. After obtaining the initial aortogram to locate the lesion, all arterial pedicles that may give rise to a radiculomedullary artery are selectively catheterized by a guiding catheter and injected. Vertebral artery injection may also be needed when a high cervical vascular lesion is suspected. Then, superselective catheterization of the feeding vessels of the malformation is achieved. Flow-directed microcatheters best overcome vessels tortuosity and are less traumatic than the standard microcatheter/wire systems, thus reducing the risk of vessel perforation.⁸⁹ The aim of the superselective catheterization is placing the tip of the microcatheter in a wedge position as far distally as possible under simultaneous biplane fluoroscopic control, avoiding traumatic arterial vasospasm. Should vasospasm occur, 2 mg of Nimodipine is injected in situ, preventing the anesthesiologist for a possible drop of the systemic arterial pressure. After checking for microcatheter redundancy that may have developed during wire progression, embolic material is delivered to the nidus of the AVM or to the fistula site of the DAVF, as close to the vein as possible.

Adjustment of LEA viscosity aids in ensuring more precise embolization.^{61,88}

Intraoperative monitoring by SSEPs is a useful adjunct and MEPs prove very helpful in case of feeding vessels arising from ASA.^{8,10,61}

Avoidances/Hazards/Risks

The major risk of the endovascular treatment of spinal AVFs and AVMs is inadvertent occlusion of a radiculomedullary artery. This invariably results in spinal cord ischemia, which is critical when an isolated hairpin shaped radiculomedullary artery rather than a supplemental artery is occluded.

In some cases, venous thrombosis may extend from veins draining the vascular malformation to veins draining the spinal cord, with consequent myelopathy.

Salvage and Rescue

Adjusted-dose intravenous heparin is used by the authors for the treatment of venous thrombosis when it extends to spinal cord draining veins, complication readily visible on angiograms.

Postoperative Considerations

Femoral puncture is generally sealed by the Angio-seal device, to reduce the risk of hemorrhagic complications and promote ambulation in embolized patients undergoing intraoperative anticoagulation, unless arterial diameter is <4 mm. Otherwise, a compression of the puncture site is mandatory, followed by placement of a compressive dressing and immobilization of the leg for 24 hours in order to avoid bleeding from the puncture site. Lower limb evaluation and peripheral arterial pulses palpation are crucial in order to detect iatrogenic arterial dissection and stenosis due to hematoma at the puncture site. In some cases, postoperative red blood cells count, hemoglobin and hematocrit are warranted to disclose hemorrhagic complications following arterial puncture, which may not be readily visible due to possible diffusion in the retroperitoneum. Good hydration is advisable pre- and postoperatively in order to reduce drawbacks following contrast injection.

Postoperative neurological evaluation is mandatory to disclose iatrogenic myelopathy due to inadvertent embolization of functional branches or extension of venous thrombosis to veins draining normal spinal cord, which

can be managed by intravenous heparin. Follow-up consists of physical examination, spinal cord MRI and spinal angiography at 3 months postoperatively. If there is no residual AV shunt, a second spinal MRI is performed at 12-month interval. Further follow-up is based on annual physical examination, unless clinical relapse warrants a new spinal MRI.

COMPLICATIONS

Main complications occurring during the endovascular treatment of spinal cord vascular malformation are: iatrogenic arterial dissection during catheterization; hematoma at the puncture site, with possible femoral nerve compression; spinal cord ischemia due to closure of radiculomedullary arteries or its branches following inadvertent migration of embolic material or vasospasm secondary to vessel manipulation; myelopathy secondary to extension of venous thrombosis to the veins draining the spinal cord; and symptoms recurrence due to incomplete treatment of the vascular lesion.

OTHER TREATMENTS

Given the success in the treatment of vascular brain malformations, radiosurgery has also been proposed as an alternative and/or third-step treatment option for spinal vascular malformation. The main indication is in those malformations, which cannot be treated by surgical and/or endovascular techniques only and with a compatible size. The first experiences of stereotactic radiosurgery seem to have led to encouraging results;⁹⁰ however, there are no large series and extensive studies, which may allow an acceptable definition of reliability of these procedures on spinal vascular malformations.

KEY POINTS

- Intradural spinal vascular malformations include a large spectrum of different conditions. The classification and description of these pathologies are often challenging and require a complete knowledge of anatomical, hemodynamic and functional features of the lesions.
- To make a nosographic differentiation of spinal vascular malformations, four different groups should be distinguished: arteriovenous fistulas, arteriovenous malformations, CMs, and aneurysms.
- The onset of symptoms can be acute in the case of subarachnoid or intramedullary hemorrhage, due

to the rupture of an AVM, or chronic and progressive in the case of a worsening myelopathy related to venous stasis and/or mass effect. The diagnosis can be obtained interpreting data from different imaging techniques as digital subtraction angiography, angio-MR and angio-CT.

- The treatment decision-making process depends on the type of lesion. Surgery plays an important role in management of spinal dural arteriovenous fistulas and AVMs located on the posterior surface of the spine. Endovascular treatment may be considered as first-line or adjunctive treatment for complex malformations.
- A multimodal approach is suggested both for the management and treatment of such challenging pathologies.

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Spinal Infections, Pyogenic Osteomyelitis, and Epidural Abscess

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Snapshot

- » Pathogenesis
- » Clinical Risk, Presentation, Radiographic Features, and Diagnosis
- » Treatment
- » Postoperative Infections

INTRODUCTION

The rate of pyogenic disc infection and vertebral osteomyelitis (PDVO) is 2 per million people per year, comprising roughly 4% of all bone infections.^{1,2} Risk factors for spine infection include diabetes, immunodeficiency, ethanol abuse, intravenous drug abuse, infection at another site, steroid use, chronic renal failure, and malignancy.³ Prior to the modern era with its common use of antibiotics, the mortality rate was as high as 25%.⁴ Spinal epidural abscesses (SEAs) are exceedingly rare at an incidence of up to 2 per 10,000 hospital admissions.⁵ For SEA, the reported mortality was nearly 100% at the turn of the century, declining to 34% by mid-century, which eventually declined further to <15% by the end of the twentieth century.⁵ Initial reports of SEA identified a poor natural history, as seen in Dandy's reported series of 32 patients in 1926, with an 81% mortality.⁶

With today's widespread use of broad-spectrum antibiotics, most cases of spinal infection are treated conservatively with antibiotic therapy, with success rates reported as high as 95%.^{1,7,8} In the largest series to date of 915 patients, the most common infectious source was thought to be from furuncles and cutaneous abscesses. The most common presenting symptom was reported to be back pain that was present in 75% of patients.⁵ Interestingly, there is some recent evidence raising questions about the seasonality of postoperative spine infections. A review by

Gruskay et al.⁹ highlights evidence for a statistically significant increase in infection during the months when spring changes to summer, while a statistical decrease in infection is noted during the change from summer to fall. They speculate that this seasonal variation may be related to an increased volume of trauma requiring surgical care in summer.

PATHOGENESIS

Pyogenic discitis refers to a bacterial infection that has involved the intervertebral disc and end plates. The most common site of hematogenously acquired osteomyelitis is the vertebrae.¹⁰ The higher incidence in children is thought to be due to the robust blood supply to the nucleus that is seen in children, but not in adults. As one ages, the blood supply recedes from the nucleus, leaving the blood supply only reaching the outer fibers of the annulus, while the nucleus relies on passive diffusion for all other nutrients.

Spinal epidural abscess is an uncommon infectious disorder, first described in 1761 by a famous Italian surgeon named Morgagni.¹¹ The diagnosis was made postmortem. Of 45 SEAs, the predominant agent was *Staphylococcus aureus*, followed by coagulase-negative *Staphylococcus* species, and less commonly *Escherichia coli*. Gram-negative organisms are thought to be of increasing prevalence as a result of increasing spread from intravenous drug abuse.²

The primary mechanism of neurologic dysfunction is thought to be compressed by the infectious mass, followed by a local inflammatory response that can lead to thrombosis of compressed epidural and spinal veins.¹² To date, animal studies of *S. aureus* epidural injections in rabbits are the most thoroughly investigated models of SEA.^{12,13} After review, the authors conclude that mechanical compression of neural structures is the main mechanism for neurologic deficit in SEA. They suggest that neurological dysfunction is typically not due to compression of anterior or posterior spinal vessels, or to vessel thrombosis that was a prevalent belief. To the contrary, many investigators argue that SEA causes vascular damage by inflammation and thrombosis, resulting in cord hypoxia and further injury.¹⁴⁻¹⁷

In the cervical and thoracic spine, epidural abscess has been considered to be a neurosurgical emergency regardless of the presence or absence of neurologic deficit, given the risk of rapid, often irreversible, neurologic deterioration, and the risks of bacteremia and sepsis. Although there is an increasing trend to nonsurgical treatment, the primary treatment for SEA often is laminectomy and epidural drainage of the abscess.^{11,18-25}

CLINICAL RISK, PRESENTATION, RADIOGRAPHIC FEATURES, AND DIAGNOSIS

Clinical Risk Factors

Schuster et al., in a systematic review of literature to identify preoperative risk factors for infection in spinal surgery, found age, obesity, diabetes, malnutrition, a higher American Society of Anesthesiologists score, posterior surgical approach, and blood transfusions to be independent risk factors for infection.²⁶ Diabetes is among the most commonly cited risk factors for spinal infection.^{11,27-36}

Presentation

It is important for the clinician not to be dissuaded by the absence of fever or white count elevation, as they are often not present. Blood cultures are a routine adjunct to diagnosis, but keep in mind that they are only positive in approximately 50–72% of cases.³⁷ Erythrocyte Sedimentation Rate (ESR) and C-Reactive Protein (CRP) markers are also useful for following the clinical progression of the treated infection, with respect to the established baseline markers.³⁸ Sensitivity of ESR is reported as high as 98% in select studies.

Reihaus et al.,⁵ in a series of 915 patients with SEA, describe a progression of symptomatology: back pain leads to radicular irritation, which progresses to weakness from compression of the neural structures, and ultimately plegia. The most common age of presentation is usually >30.⁵ In 1948, Heusner and colleagues described the early stage is local inflammation and tenderness, followed by local signs of nerve irritation: Laseague's, Brudzinski, Kernig's, and Lhermitte's signs. Back pain was reported quite commonly in several large patient series. In the literature, the prevalence of radiculopathic features ranges from 12% to 47%.^{28,30} Roughly one quarter of patients present to the emergency setting with incontinence and paraplegia. Rectal tone, volition, and strength are important to document; as many as 38% of patients have urinary incontinence on presentation.^{11,33,39}

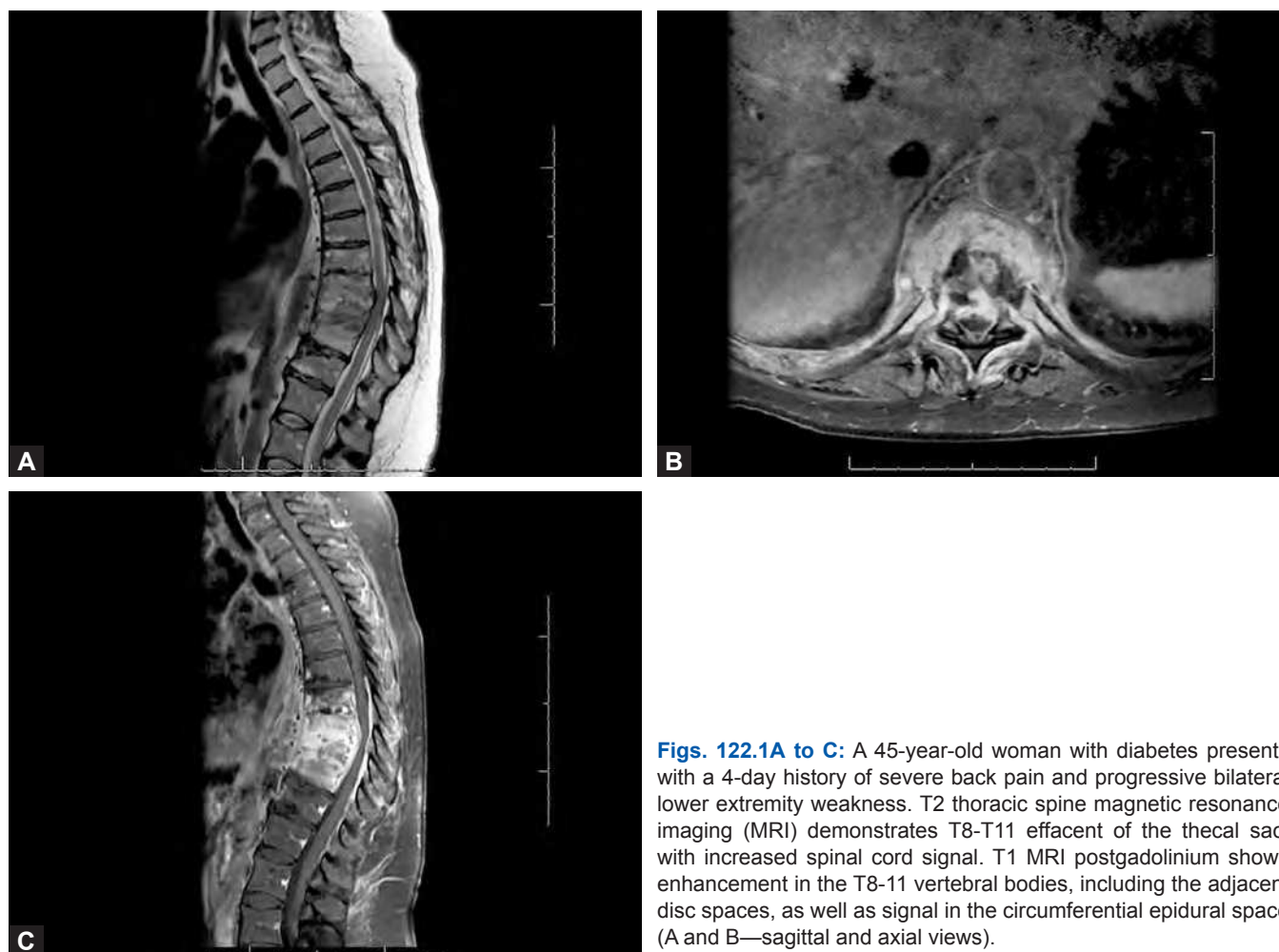
Magnetic resonance imaging (MRI) often with gadolinium contrast is the standard of care, and is sensitive even at the earliest stages.^{5,39-42} In a series of 20 consecutive patients with SEA, MRI demonstrated a heterogeneous collection in the epidural space, with a thick, peripherally enhancing collection of pus associated with local engorgement of the epidural venous plexus⁴² (Figs. 122.1A to C). spinal intramedullary^{43,44} and subdural abscesses are exceedingly rare.⁴⁵⁻⁴⁹ Lastly, computed tomography (CT)-guided biopsy is a helpful nonoperative diagnostic measure in up to 68% of cases, and this percentage is slightly higher when the cultures are taken intraoperatively.³⁷

TREATMENT

The indications for surgery for PDVO are neurologic compromise, mechanical instability, intractable pain, failure of antibiotic therapy, and the need to achieve a definitive diagnosis. In some cases, a SEA itself is indication enough for surgical treatment.⁵⁰ A SEA in the absence of discitis or osteomyelitis is usually treated with laminectomy without instrumentation and fusion. When the infection is severe, the postoperative placement of drains in the epidural space may be used for monitoring and continued drainage of pyogenic collections.

Instrumentation in the Setting of Infection

Despite the concern for bacterial colonization of foreign body implants, instrumentation in the setting of infection has been shown to be safe and beneficial to patients.⁵¹⁻⁵⁶



Figs. 122.1A to C: A 45-year-old woman with diabetes presents with a 4-day history of severe back pain and progressive bilateral lower extremity weakness. T2 thoracic spine magnetic resonance imaging (MRI) demonstrates T8-T11 effacement of the thecal sac, with increased spinal cord signal. T1 MRI postgadolinium shows enhancement in the T8-11 vertebral bodies, including the adjacent disc spaces, as well as signal in the circumferential epidural space (A and B—sagittal and axial views).

Lee et al.⁵⁷ in a retrospective review of >100 patients with pyogenic spine infections found a total of 30 patients requiring instrumentation. They concluded that the practice was effective for debridement of infection without recurrence. Moreover, postoperative stability was demonstrated with an effective fusion in 29 patients. Rayes et al.³ treated 47 patients with instrumentation and radical debridement for the indication of failure of response to antibiotic therapy and mechanical instability in the setting of spinal infection. The majority of these patients underwent anterior approach for the simultaneous decompression of the spinal canal and debridement of an infectious intervertebral process. All patients had improvement in American Spinal Injury Association (ASIA) grade at the time of discharge. Two patients developed recurrent infection and only one of those two patients required removal of instrumentation.

Cage Placement

Kyphosis after anterior debridement for vertebral osteomyelitis is a concern. Typically, many spinal surgeons use autograft or allograft tricortical iliac crest, less commonly employing fibular, femoral or rib strut grafts to provide structural support in the defect created by ventral debridement.⁵⁸ Posterior spinal instrumentation is often then provided as a second-staged procedure to facilitate stability and fusion.⁵⁹⁻⁶³ There is a growing body of literature to support the safe usage of titanium cage placement for anterior column support in the setting of instability with superimposed infection. Rosner et al. reported the results of a retrospective series of 21 patients, all of whom underwent anterior corpectomy and titanium mesh cage placement supplemented with allograft and demineralized bone matrix, followed by posterior instrumentation and fusion. Typically,

the posterior instrumentation spanned one to two levels above and below the site of corpectomy. An average of 13° of sagittal alignment was restored. Titanium was used by the author with the thinking that it may be less prone to colonization than bone or polymethylmethacrylate, given the decreased porosity of titanium. Hee et al.⁶² treated seven patients with titanium mesh cages packed with autograft followed by immediate posterior instrumentation, with excellent results, and without recurrent infection.

Anterior versus Anterior/Posterior Two-stage Approach for PVDO

To date, there are no prospective studies comparing anterior, posterior or combined approaches for the treatment of PDVO. Many spinal surgeons have felt that anterior or lateral approach to the treatment of anterior column pathologies such as pyogenic vertebral osteomyelitis and osteodiscitis is adequate. Addition of the posterior approach is justified by the belief that there is no direct contamination of the operative field by infection, although this theory has not been thoroughly investigated.

Still, there are many spine centers that feel that posterior spinal instrumentation is necessary to provide additional support. One counter-argument is that the surgeon should take all precautions to shorten the interval of malnutrition caused by spine infection and provide the most conservative surgical correction possible. The second-staged posterior approach may have an increased infection risk and prolong the malnourished state, putting the patient at increased risk for wound breakdown.⁶⁴ Dimar et al.⁵⁹ report good results with a delayed period prior to the second-staged posterior instrumentation by allowing for critical optimization of cardiac and respiratory status.

Single-stage Combined Anterior/Posterior Approach

Sharan and Przybylski reported a series of 17 patients treated for PDVO and discitis with a single-staged anterior debridement with iliac crest graft placement followed by posterior instrumentation and fusion.⁶⁵ Fountain published a series of 17 patients who were treated in a single-staged, combined anterior debridement with bone graft placement followed by posterior instrumentation and Harrington rod placement. He found a return to ambulation in all patients by 14 days and only one postoperative

recurrent infection and one hardware failure by 6-month follow-up.⁶⁶ Redfern et al.⁶⁷ utilized anterior debridement and posterior rod placement. They reported adequate postoperative pain relief and no recurrent infections on follow-up. Furthermore, Graziano and Sidhu⁶¹ achieved successful incorporation of the strut graft in all seven patients treated with combined anterior corpectomy and posterior instrumentation.

POSTOPERATIVE INFECTIONS

Postoperative wound infections can be classified as early or late, with 1 month being the cutoff point. An extensive review of >15,000 instrumented fusions found a postoperative infection risk of 8.5% and 12.2% in revision surgeries.⁶⁸ The average time for presentation was found to be 2 weeks. The most common pathogen responsible for spine infections is *S. aureus*, followed by *S. epidermidis*, *Propionibacterium acnes*, and *Corynebacterium*. The most common symptom is almost always severe pain, with the most common exam finding being wound drainage.

The Scoliosis Research Society in a 5-year database of spinal procedures calculated a surgical site infection rate of 2.1%.⁶⁹ It further stratified patients based on primary diagnosis, and found rates as high as 4% for patients with kyphosis. The significance of kyphosis may lie in the extent of surgery, in which deformity corrective measures for kyphosis carry longer operative times, increased estimated blood loss (EBL), and more involved spinal procedures. Significant risk factors for infection include the use of instrumentation, fusion, and revision surgery. When comparing open surgery versus minimally invasive approaches for both discectomies and transforaminal interbody fusions, the minimally invasive cohort carried a lower infection rate.⁶⁹ This is thought to be related to the fact that minimally invasive spine procedures often have smaller incisions and confer less tissue devascularization and damage. In the hands of the experienced surgeon, the surgical times would also be equivalent. One bias of these studies is that the majority of these studies are produced by proponents of minimally invasive spine surgery.

Olsen et al., in a retrospective review of patients undergoing laminectomy or fusion, found a surgical site infection rate of 2.8% over a 5-year period. Also, independent risk factors for infection were found to be posterior approach, tumor resection, postoperative incontinence, and morbid obesity.

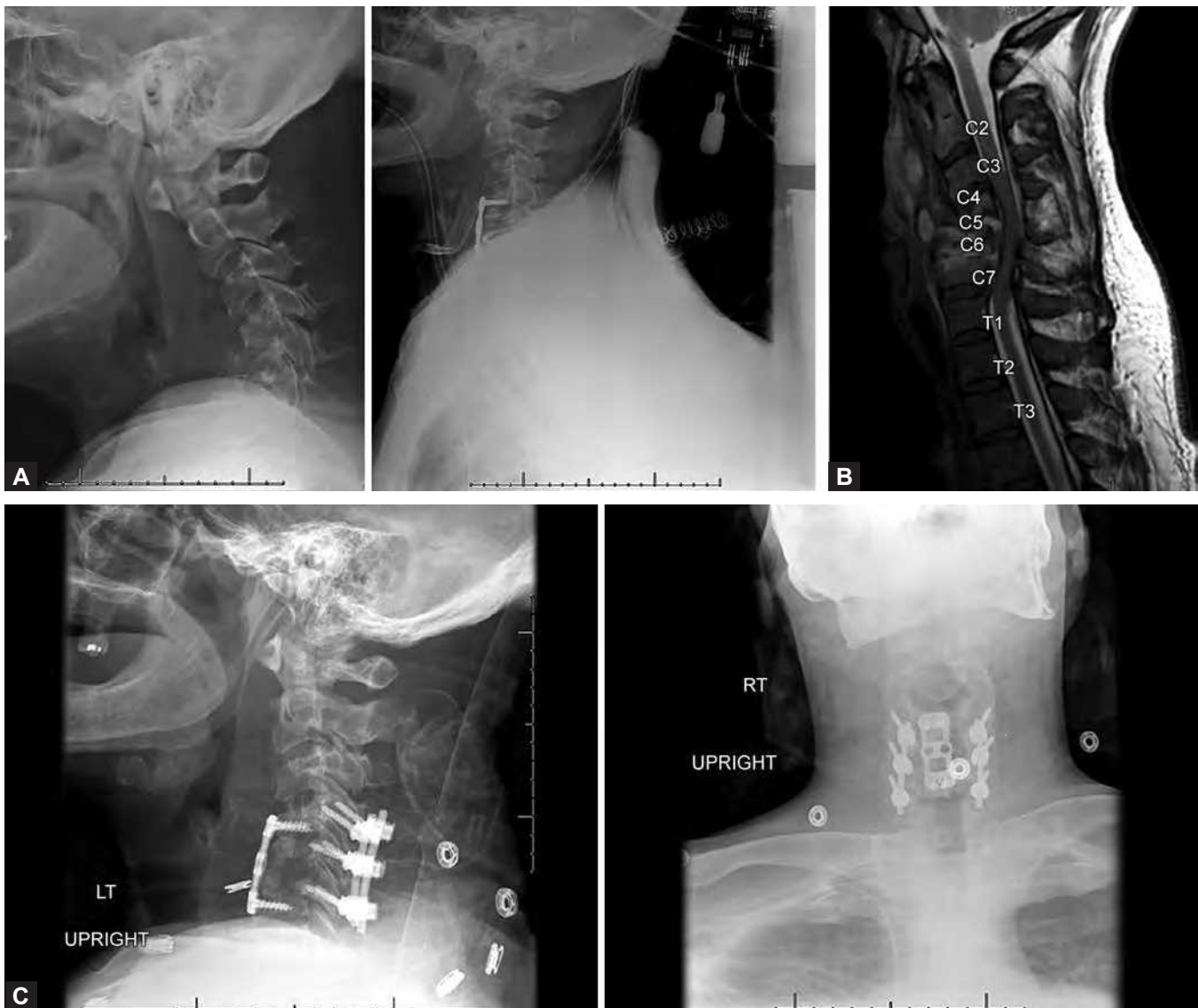


Figs. 122.2A to D: A 30-year-old man with a history of intravenous drug use, and recent 2-day history of fevers presents with bilateral leg pain and urinary incontinence. Initial computed tomography scan shows erosive end plate changes at L4-L5 and L5-S1(A). L4-L5 and L5-S1 osteodiscitis with a circumferential dorsal epidural abscess on MR T2 and T1 post-gad imaging is seen (B and C). Circumferential epidural abscess was debrided, as well as in the interbody of L4-5 and L5-S1. Given the concern for mechanical instability noted intraoperatively, L4, L5, and S1 pedicle screws were placed [ap, radiograph, lumbar spine (D)].

Evidence for Removal of Hardware in Surgical Site Infections

The concern for foreign bodies in the setting of infection is its resistance to antibiotic therapy. One method of resistance to antibiotic therapy proposed is the formation of a glycocalyx biofilm layer over implants that form a shield resistant to antibiotic penetration.⁷⁰ Postoperative wound infections have a definition that varies from study to study. Wound drainage, radiographic findings, fever, and abnormal laboratory values all contribute to the suspicion of wound infection. Surgical treatment often involves, at minimum, debridement of nonviable

tissues and bone graft with placement of subfascial (Figs. 122.2A to D) and/or epifascial drains to monitor and drain wound collections. Intuitively, a solid fusion demonstrated by CT imaging in the setting of postoperative infection may make removal of posterior instrumentation an easy decision. Some clinicians argue for the removal of instrumentation in all cases of postoperative infection.⁷¹⁻⁷³ Sonntag et al.⁷⁴ argued that the instrumentation can be left in place to promote fusion, and demonstrated that this was safe practice in combination with antibiotic-fluid suction/irrigation systems placed after operative debridement of nonviable tissues, including infected bone graft (Figs. 122.3A to C).



Figs. 122.3A to C: A 56-year-old man with a C5 compression fracture with resulting kyphotic deformity fracture (A). Magnetic resonance imaging demonstrating cord signal edema from compression (B). Restoration of lordosis is achieved after C5 corpectomy, placement of tricortical iliac strut autograft, followed by short segmental posterior cervical decompression and fusion (C).

CONCLUSION

Definitive operative recommendations for PDVO and SEA are unavailable, given the lack of randomized controlled trials as well as the absence of prospective data. Also, the absence of a standardized methodology for characterizing spinal infections makes comparison of various studies challenging. Moreover, the definition of surgical site infection varies across the literature.

There is, however, strong evidence supporting surgical debridement of PVDO and SEA, as well as anterior column

reconstruction with bone graft or cage placement when there is substantial anterior bone and disc destruction and resultant instability, deformity, or a large anterior abscess. Posterior instrumentation is commonly performed for definitive stabilization after corpectomy or discectomy, though there is little evidence either way for this practice or for its timing. Most of the evidence gathered above does not support the claim that instrumentation in the setting of infection provides a risk for recurrent infection at 1–2 years follow-up.

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- Przybylski and Sharon report 17 patients with PDVO, treated in a single-stage, anterior posterior decompression and fusion. The authors find that this practice is tolerated, and could provide an alternative to a staged approach, with the goal to limit hospital stay and morbidity.

Spinal Tuberculosis

S Rajasekaran, Rishi Mugesh Kanna, T Ajoy Prasad Shetty

Snapshot

- » Pathogenesis
- » Clinical Features
- » Differential Diagnosis
- » Investigations
- » Treatment
- » Surgery in Healed Tuberculosis

INTRODUCTION

Spinal tuberculosis (TB) accounts for >50% of skeletal TB and is caused by the organism *Mycobacterium tuberculosis*.¹ The predilection of the microbe to affect the vertebral column is next only to the lungs and can be correlated to the high vascularity of the vertebral marrow. Spinal disease is most frequently located in the lower thoracic and thoracolumbar junction (50–70%).² Thoracic disease is more common in children and adolescents, whereas lumbar disease is found commonly in adults. The proximity of the cisterna chyli and the lungs, and the thoracolumbar junction being a transitional region between the stable thoracic spine and mobile lumbar spine makes this region favorable for bacterial lodging. Most cases of bone and joint TB are isolated to one area, but multifocal disease has also been described in up to 16% of patients.

The advent of chemotherapy has significantly improved the outcome of patients with TB. If initiated early, most complications of spinal TB such as neurological complications and deformity can be avoided by adequate chemotherapy. It is essential to understand that spinal TB is predominantly a medical disease, and surgery is indicated only in select situations.

PATHOGENESIS

Tuberculosis is caused by a bacillus of the *M. tuberculosis* complex. The most common of the group, *M. tuberculosis*,

grows slowly and stains acid fast because of a highly lipid and peptidoglycan-rich cell wall. It is a slow-growing aerobic organism with a growth-doubling time of about 20 hours in conditions favorable to the bacillus. In unfavorable conditions, it can grow only intermittently or remain dormant for a prolonged period.

Vertebral infection by the bacillus results from hematogenous dissemination from a primary focus, and associated active focus can be identified in only <10%. The primary focus may be active or quiescent, apparent or latent, and are usually in the lungs, lymph glands of the mediastinum, mesentery or cervical region, kidney or other viscera. Spread occurs to the vertebra through the blood stream along the arterial system. Alternatively, tuberculous bacilli may travel from the lung to the spine through the Batson's paravertebral venous plexus or by lymphatic drainage from the para-aortic lymph nodes.

Microscopic Features

Following the infection in the vertebral marrow, the initial inflammatory response is characterized by accumulation of polymorphonuclear cells, which are slowly replaced by macrophages and monocytes. The tubercle bacilli are phagocytosed and their lipid is dispersed throughout the cytoplasm of macrophages, transforming the macrophages into *epithelioid cells*. Epithelioid cells are characteristic of the tuberculous reaction. These are large, pale cells with

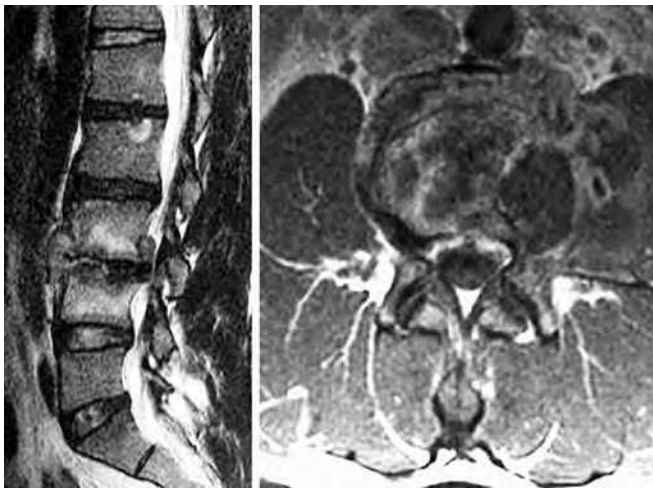


Fig. 123.1: Sagittal and axial magnetic resonance imaging demonstrate paradiscal type of lumbar tuberculosis with damage to the vertebral endplates and extension of infection into the vertebral bodies.

a large vesicular nucleus and abundant cytoplasm. Their phagocytic capacity is subdued and they become more secretory in nature. Another characteristic feature of tuberculous lesion is the presence of *Langerhans giant cells*, which are formed by the coalescence of a number of epithelioid cells and whose presence on pathological analyses may be helpful from a diagnostic point of view. Cellular immunity is mediated through lymphocytes, which form a ring around the peripheral part of the lesion and attempt to control the proliferation of the bacilli. This typical lesion of TB formed by the reactive cells of the reticuloendothelial tissues (the macrophages, epithelioid cells, Langerhans giant cells, lymphocytes, and inflammatory exudate) constitutes the *tubercle*. With progressive destruction, caseation occurs in the center of the tubercle due to coagulation necrosis. Presence of caseation necrosis is a diagnostic feature of TB. Adjacent tubercles then coalesce to form a large abscess filled with caseous material containing serum, leukocytes, caseous material, bone debris, and tubercle bacilli and lined by thin reactive capsule. Since it is a chronic infection, the acute features of inflammation like warmth and redness are absent and hence this abscess is termed as the *cold abscess*.

Macroscopic Features

The *Mycobacterium bacilli* reach the vertebra either through the vascular or lymphatic system and lodge in the subchondral marrow on either side of the disc due to the specific arterial anatomy of the paradiscal region. This is

the most common pattern of tubercular spinal infection called the “paradiscal” type (Fig. 123.1). The other types of TB are the “centrum” type (predominant vertebral body destruction), posterior type (predominant involvement of posterior elements) (Figs. 123.2A to C), and the nonosseous type (where bony destruction is less with extensive abscess formation). In the classic “paradiscal” type, the intervertebral disc is not involved primarily because it is an avascular structure. But progressive destruction of the vertebral end plates on both sides of the disc affects the nutrition of the disc, leading to collapse of the disc space. In the early stages, there is marked increase in the vascularity of the bone and hence severe osteoporosis ensues. Due to progressive destruction by the tuberculous bacilli and osteoporosis, there is osteolysis leading to compression, collapse, and deformation of the bones. Necrosis also takes place due to ischemia secondary to arterial occlusion. Vertebral body collapse leads to local kyphosis and retropulsed bony fragments can compress the spinal cord. In children, extensive involvement with complete destruction of many adjacent vertebral bodies may be seen.

Due to the chronic inflammatory response and the secretory nature of the epithelioid cells, extensive abscess formation is typical of TB, and spreading abscess formation in the epidural, prevertebral, and paravertebral regions is common. Extension of abscess into the epidural space can result in neurological symptoms and signs (Fig. 123.3).

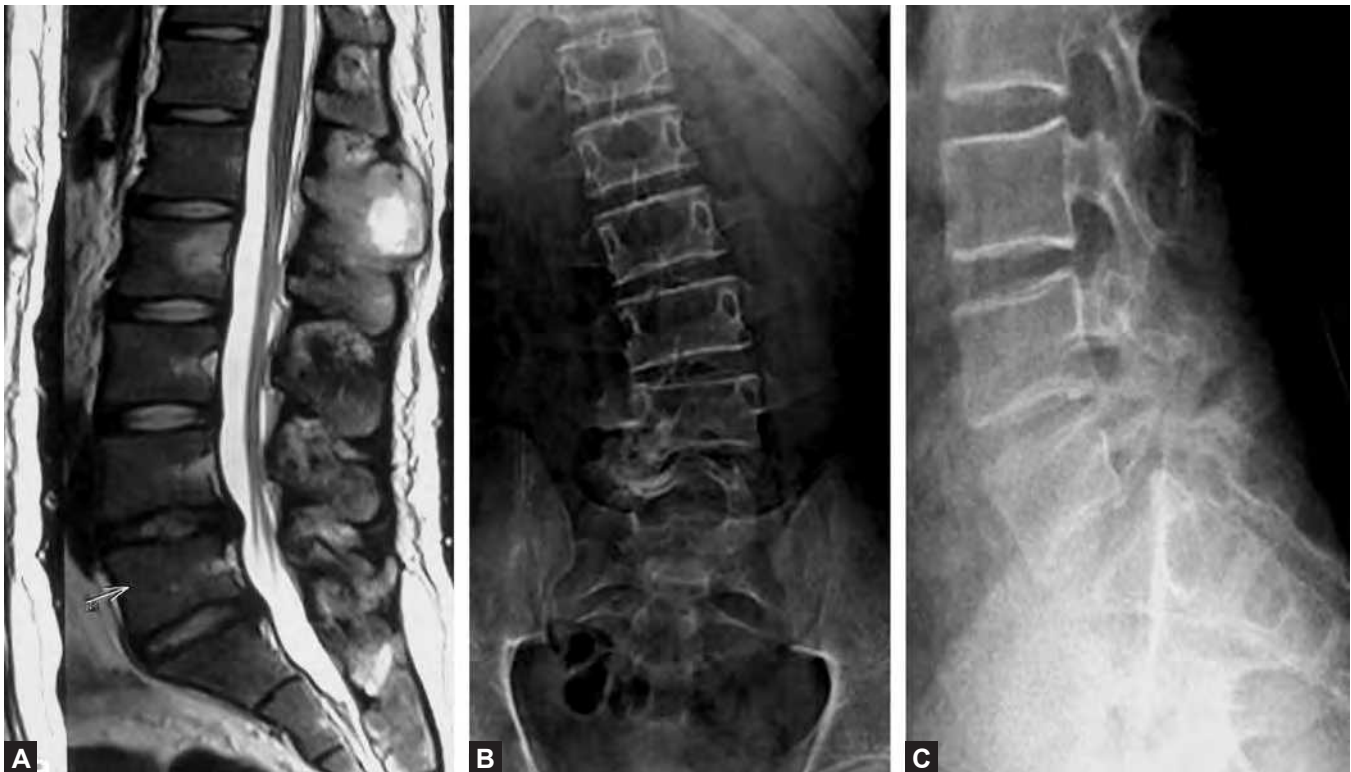
CLINICAL FEATURES

Epidemiology

Spinal TB is common in the developing parts of the world among the lower socioeconomic strata. Crowding, lack of sanitation, reduced access to health care, and poor education are the reasons for the higher incidence in these regions. In developed nations, immunosuppression due to HIV, old age, and cancer chemotherapy has resulted in an increase in the incidence of TB of late. While spinal TB is common during the first three decades of life in developing nations, it affects the adults and elderly in the developed nations.

Systemic Involvement

It is important for the treating physician to understand that TB is a systemic disease and infection of multiple organs can coexist. An active concomitant primary tubercular infection elsewhere in the lungs, lymph nodes,



Figs. 123.2A to C: Posterior element tuberculosis. Tuberculosis of the spinous process of the L1 vertebra (A). Another patient with tuberculosis of the lumbar facet joint leading to anterior subluxation (B and C).



Fig. 123.3: Posterior epidural abscess of the thoracic spine causing cord compression. This is the only indication for an isolated laminectomy in a patient with Pott's spine.

intestines, ovaries, kidneys should be looked for. In spinal TB, multiple segments of the spine can be afflicted at the same time (Fig. 123.4). Though the presenting symptoms

and signs are usually due to one particular lesion, magnetic resonance imaging (MRI) of the whole spine often identifies multiple noncontiguous lesions in many patients. The incidence of such multifocal spinal TB varies from 1.1% to 71% depending on the type of investigation used to evaluate the spine.³ The reported incidence in centers that do not perform routine, whole-spine MRI is 1.1–10% using a combination of regional radiography, computed tomography (CT) and MRI, and 16% using 99 mTc-MDP bone scan and 71.4% when whole-spine MRI was undertaken.³ The lesions can be either in continuity or with skipped single or multiple uninvolved segments.

Pain in Spinal TB

Unlike pyogenic spondylitis, tuberculous lesions have a much more insidious onset and the clinical symptoms often develop over a period of 1–2 months. Back pain localized to the affected site and aggravated with spinal movements is the usual presenting feature. The back pain in TB can be attributed to chronic inflammation, segmental instability, distension due to abscess and pressure on



Fig. 123.4: Sagittal whole-spine magnetic resonance imaging demonstrates multilevel spondylodiscitis in the cervical, upper thoracic, and lumbar regions (arrows). The presenting symptoms were due to the lesion at the thoracic region.

neighboring structures. With development of instability, the pain changes in character and becomes quite severe. Patients may need to support their trunk by placing their hands on the couch while sitting (*tripod sign*) or hold the neck by their hands when the cervical spine is affected (Fig. 123.5). Rest pain at the affected region and sudden exacerbations (night cries) during sleep due to lack of protective muscle spasm are also common.

Radicular pain is an uncommon feature and if present, indicates compression on the nerve roots due to abscess or free bone fragments. Sometimes radicular pain along the thoracic nerve roots may be referred to the abdomen leading to misinterpretations as cholecystitis, pancreatitis, appendicitis, and renal diseases.

Constitutional symptoms of malaise, loss of appetite and weight, evening rise of temperature, and night sweats are also common but are more typical of pulmonary TB. These constitutional symptoms are observed in <40% of cases of spinal involvement and are more common in patients with associated malnutrition.⁴ Extensive disease can be present with minimal systemic disturbances in patients who have good immunity and nutritional status (Fig. 123.6).



Fig. 123.5: Cervical instability in a child due to upper cervical tubercular destruction. The child needs to support his neck to reduce instability pain.

Cold Abscess

A paravertebral cold abscess is a diagnostic feature of spinal TB and is observed in at least of 50% cases of spinal TB.⁵ It may be clinically evident, either in the paraspinous area or may tract distally depending on the region of involvement. The abscesses initially collect within the infective focus and may track along the perineural, perivascular, intermuscular, subpleural, subperitoneal, and natural areolar tissue spaces to present remotely away from the vertebral lesion (Table 123.1). Depending on the location, the abscess may collect either in the deeper planes or present superficially.

The common presentation includes the paravertebral abscesses in the thoracic spine tracking the intercostal neurovascular bundle along the chest wall, retropharyngeal abscess from a cervical lesion, and presacral and pelvic retroperitoneal abscess from a lumbar lesion. A psoas abscess usually arises from thoracolumbar tuberculous lesions below the diaphragmatic attachment to the spine. Psoas abscesses are pathognomonic of spinal TB and can present bilaterally in various sizes (Figs. 123.7A and B). Cold abscess can also present in the inguinal region commonly or can track distally into the thigh or calf region rarely (Figs. 123.8A to D). Lumbar psoas abscesses can also present at the Petit's triangle, in the ischioanal fossa and in the buttock under gluteus maximus. The abscess can spread along the perineural spaces, e.g. from the cervical spine, along the brachial plexus sheath into

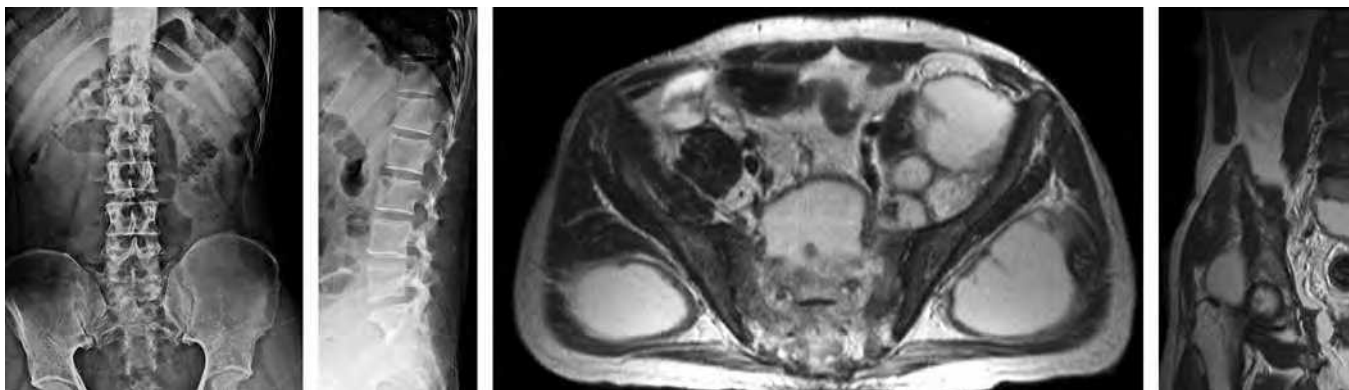
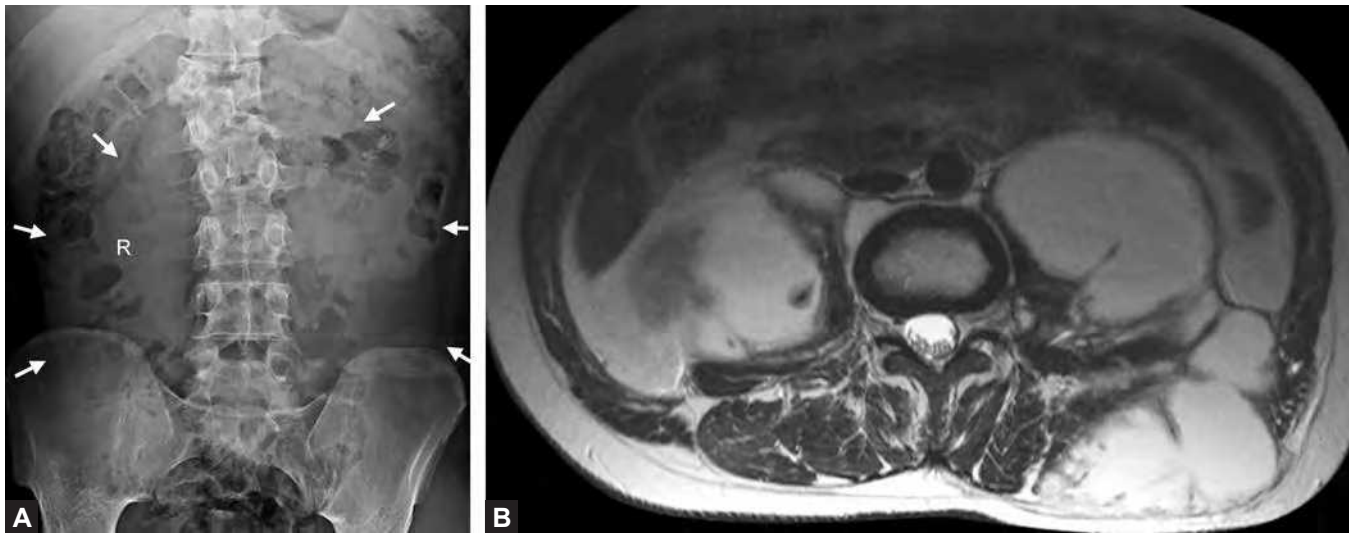
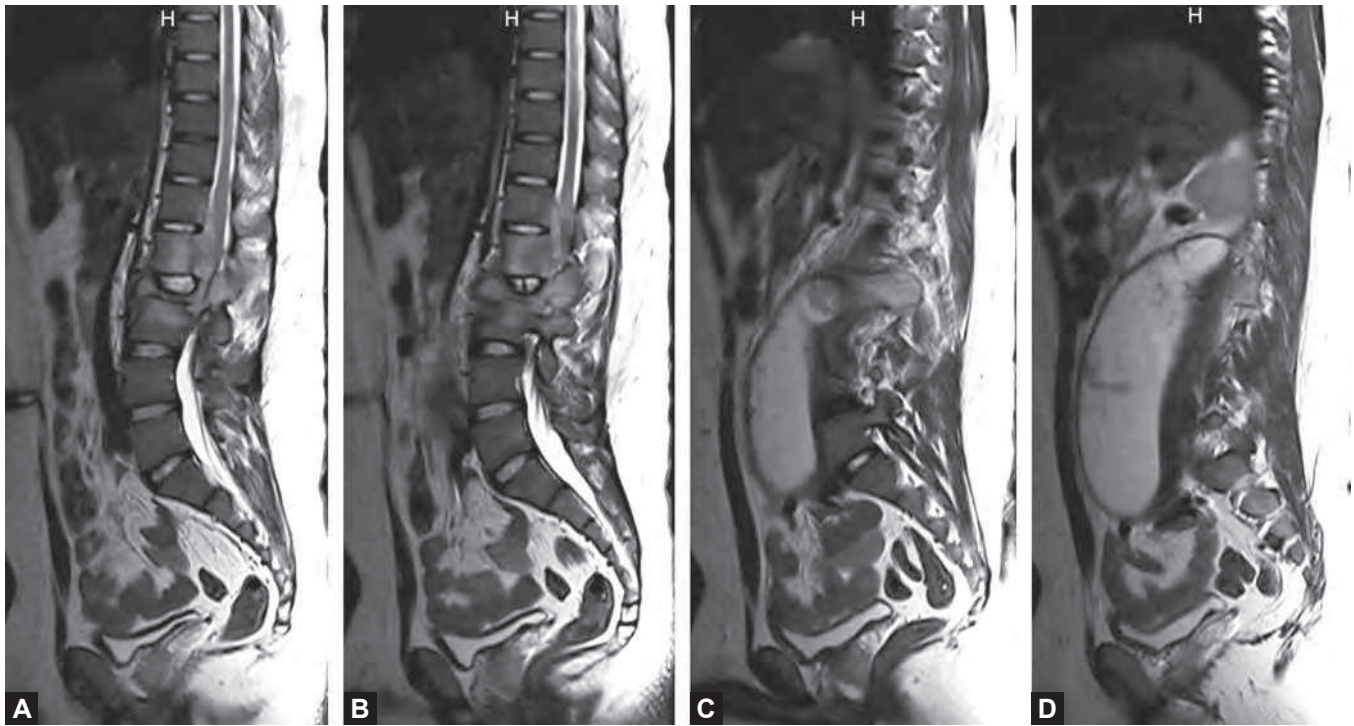


Fig. 123.6: The extent of abscess formation in tuberculosis does not match the severity of vertebral damage. The lumbosacral radiographs of this patient do not show any vertebral damage. But the patient has extensive abscesses collected in the paravertebral, pelvic, and iliac regions. Except for back pain, he was asymptomatic.

Table 123.1: Location of cold abscess and their pathways of spread from the primary spinal focus.	
<i>Paths of spread</i>	<i>Presenting region</i>
Cervical spine	
Prevertebral fascia	Retropharyngeal abscesses
Prevertebral fascia	Mediastinum to enter trachea, esophagus, or pleura
Deep cervical fascia	Posterior to the sternomastoid muscle (posterior triangle of neck)
Thoracolumbar spine	
Intercostal nerves	Chest wall
Ilioinguinal and iliohypogastric nerves	Rectus sheath and lower abdominal wall
Psoas sheath	Thigh
Posterior spinal nerves	Paraspinal region
Superior gluteal nerve	Buttock
Flat muscles of abdominal wall	Petit's triangle
Internal pudendal nerve	Ischiorectal fossa



Figs. 123.7A and B: Huge bilateral psoas abscess (arrows) in a patient with thoracolumbar tuberculosis (A). The anteroposterior radiograph shows paraspinal soft tissue widening due to the abscess which is confirmed in the axial magnetic resonance imaging (B).



Figs. 123.8A to D: The tracking of a psoas abscess shown through serial sagittal images. The abscess that develops in the disc and adjacent vertebral body (A), tracks along the neural foramen and the psoas sheath (B and C), and forms a huge paravertebral psoas abscess (D).

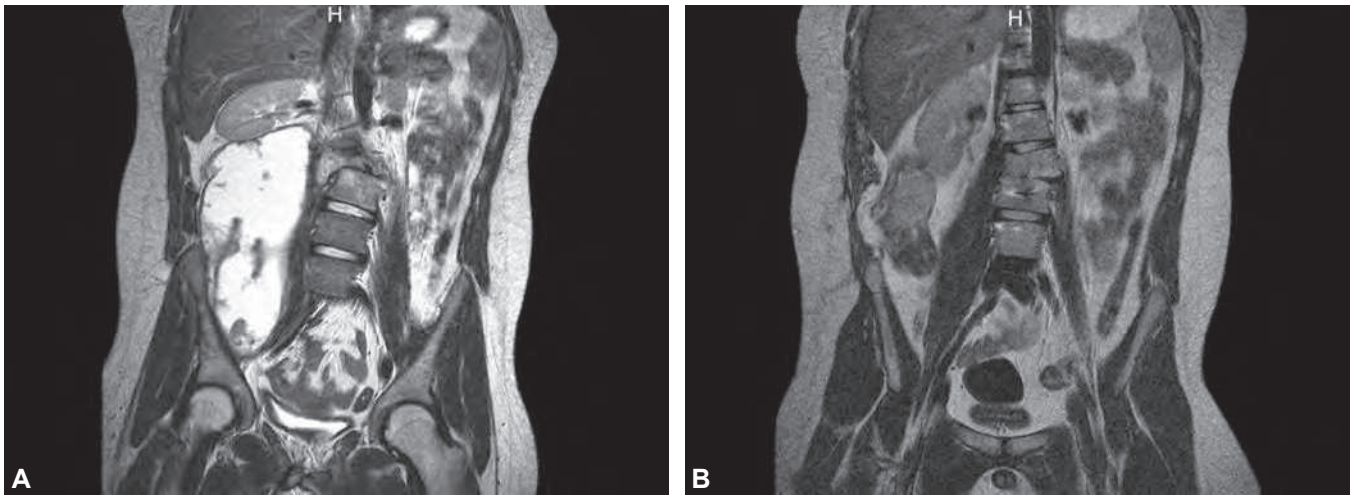
medial side of arm, from the sacroiliac joint along the sciatic nerve into the gluteal region, posterior thigh and the calf muscles. It can also spread along the perivascular spaces (e.g. along the aorta and its branches, along the femoral vessels into the thigh, either deep along the femoral canal or present superficially in the femoral triangle, along the obturator vessels into the adductor region, along the branches of internal iliac vessels into the gluteal region, along the brachial artery into arm, etc.).

Deeper abscesses are not clinically palpable but can present with pressure symptoms. A retropharyngeal abscess arising from cervical TB can produce dysphagia and dysphonia. Some posterior compartment abscesses in the erector spinae and those from the sacroiliac joints can be palpable. They may present as a tender fullness elevating the overlying muscles. Abscesses presenting superficially have the typical features of cold abscesses. Abscesses in patients treated early with antitubercular chemotherapy resolve gradually (Figs. 123.9 and 123.10). If left untreated, thinning of the skin by pressure and inflammation can result in rupture of abscess. Once the abscess contents are discharged, persisting infection in the walls of the abscess

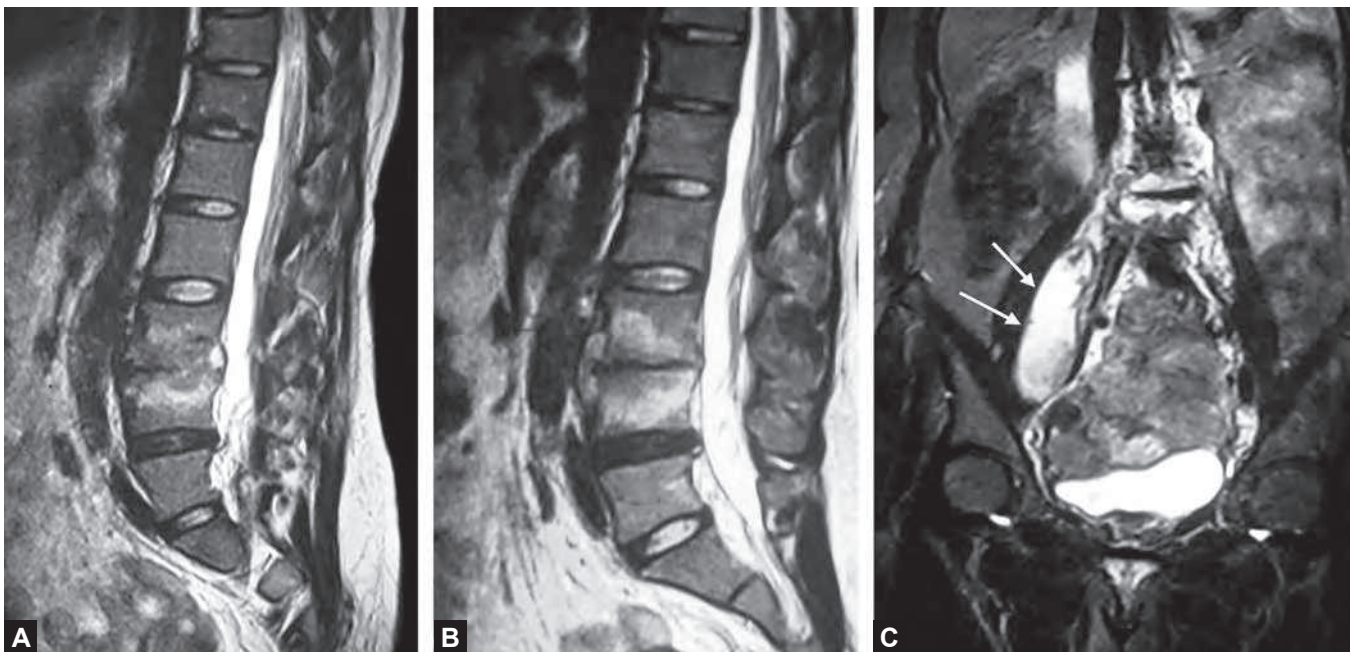
cavity leads to the formation of a sinus. The sinus may heal spontaneously after all the necrotic material is discharged or may continue for long periods if there is any residual pyogenic or tubercular infection (Figs. 123.11A to E). The tubercular pus is white or light grey in color, watery, and has no specific smell unlike a pyogenic abscess.

Tubercular Kyphosis

As the disease progresses, collapse of the vertebral body is evident as a localized kyphotic deformity. Significant involvement of a single vertebral body manifests as a prominence of a single spinous process termed as a knuckle deformity. Involvement of two or three adjacent vertebral bodies manifests as a sharp, angular kyphosis called the *gibbus* and involvement of multiple adjacent vertebrae manifests as *global rounded kyphosis*. With progressive destruction and further destabilization, sagittal, coronal subluxations, or rotatory translations can occur, leading to catastrophic neurological complications. Lesions of the cervical and lumbar region tolerate vertebral destruction without evident kyphosis due to their inherent lordosis, whereas thoracic lesions present earlier with significant



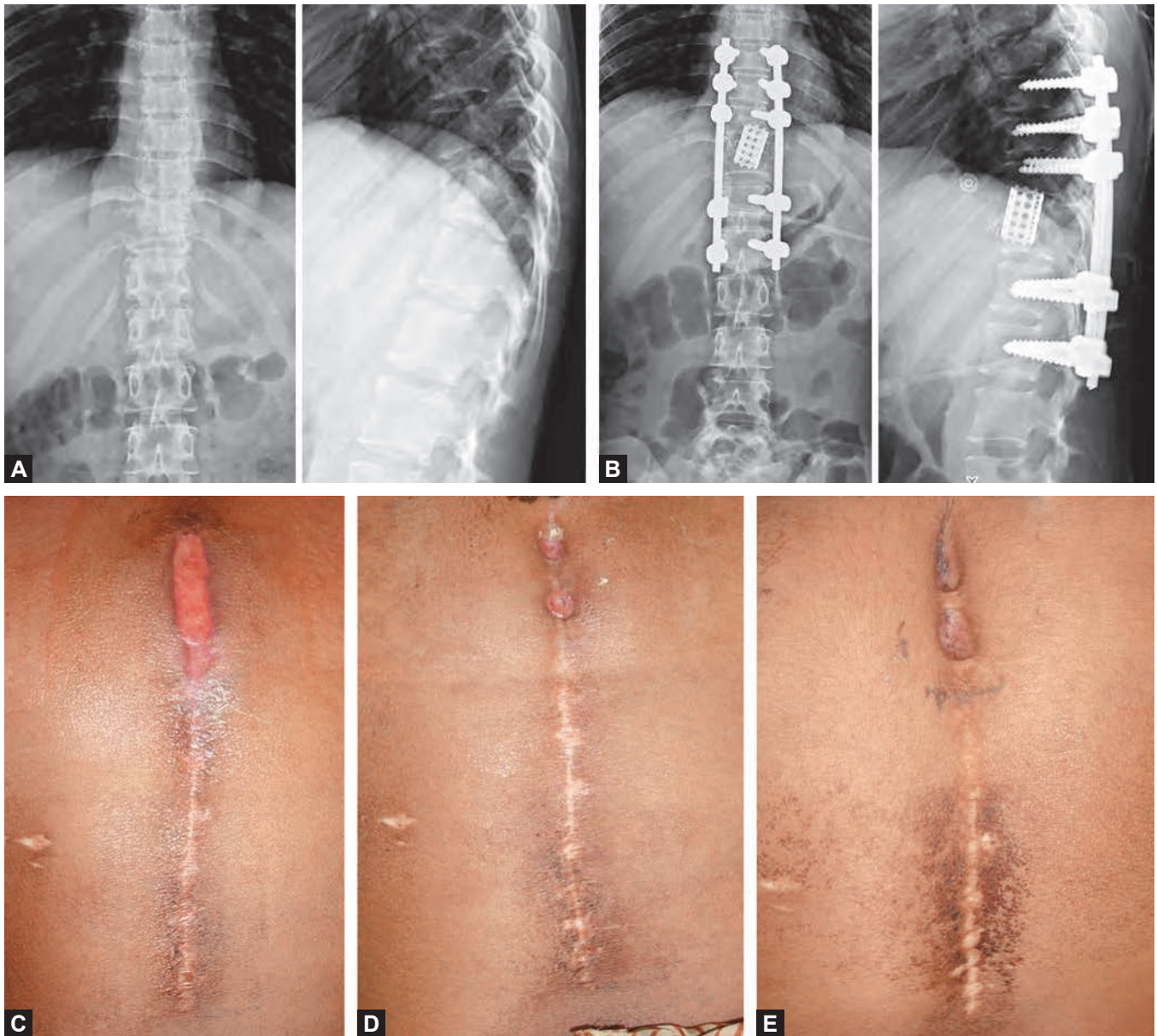
Figs. 123.9A and B: Resolution of abscess following appropriate antitubercular treatment. The coronal and sagittal magnetic resonance images show resolution of the huge paravertebral psoas abscesses and the epidural abscess after successful antitubercular chemotherapy and surgical stabilization. Coronal magnetic resonance image of a patient with huge paravertebral psoas abscesses on the right psoas muscle is shown in (A). The abscess has completely resolved in the follow-up MR image (B) after successful anti-tubercular chemotherapy and surgical stabilization.



Figs. 123.10A to C: Sagittal magnetic resonance imaging (MRI) of a patient with L3–L4 tubercular spondylodiscitis (A). The patient was treated with adequate chemotherapy and declared healed after 9 months. Follow-up MRI performed at 3 years shows fatty replacement of the vertebral body and healing of the lesion (B). However, coronal MRI shows the presence of residual cold abscess on one side (C). These abscesses are considered “sterile” and are not treated by medical or surgical methods, if the patient does not have any clinical features of disease activity.

deformity. Uncommon types like the posterior element involvement and the nonosseous type do not present with kyphotic deformity.

In all patients, the kyphosis progresses during the active stage of the disease and the final deformity is related to the extent of vertebral body loss and the spinal level



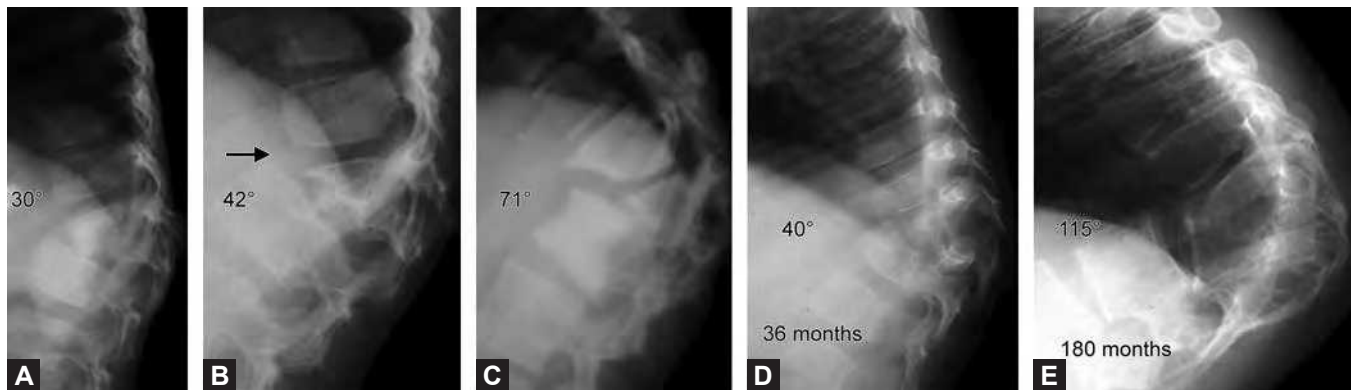
Figs. 123.11A to E: Typical healing of a tuberculous sinus. Posterior surgeries for active spinal tuberculosis carry a risk of persistent abscess drainage with delay in wound healing. This patient with T10-T11 tuberculosis had been treated by posterior stabilization and global reconstruction (A and B). The patient developed a sinus through the surgical site. Clinical photographs of the sinus taken at 6 weeks (C), 12 weeks (D) and 4 months (E) show good healing of the sinus eventually with continuous chemotherapy.

of involvement. Complete destruction of each vertebral body can account for a final kyphosis of approximately 30° and this is a little more in the children and thoracolumbar junctional lesions. In children, the kyphosis continues to progress until the period of growth is complete (Figs. 123.12A to E). Hence, all children need continued follow-up till the entire growth potential is completed. Rajasekaran has described the “spine at risk” radiographic signs where

children at potential risk for progressive kyphosis can be identified at an early stage (described later).

Neurological Deficit

Neurological involvement occurs in up to 20% of the patients with spinal TB.⁶ Since thoracic and the thoracolumbar regions are the common regions afflicted



Figs. 123.12A to E: Lateral radiograph of thoracolumbar spine of a child with spinal tuberculosis treated by chemotherapy. The kyphosis angle is 30° at the end of treatment that progressively has worsened to 115° at the end of 15 years. Post-tubercular kyphosis can worsen in children and can be effectively predicted and prevented by looking for the “spine-at-risk” signs. This child has had posterior retropulsion and toppling sign positive and hence has developed progressive kyphosis.

Table 123.2: Stages of tuberculous paraplegia.

Patient is asymptomatic Neurological examination reveals an extensor plantar response or ankle clonus
↓
Patient has incoordination while walking but can walk with support
↓
Patient is confined to bed due to severe spastic weakness (“paraplegia in extension”) Varying degrees of sensory blunting present
↓
“Paraplegia in flexion” with bladder, bowel involvement, and flexor spasms
↓
Flaccid paraplegia

by TB, lower limb weakness with bladder and bowel involvement are the usual neurological symptoms. Neurological involvement initially presents as incoordination and clumsiness while walking and slowly progresses to paraplegia (Table 123.2). Cervical tuberculous lesions manifest with quadriparesis.

Neurological deficits can occur both in the active phases of the disease and even after complete healing. In active lesions, it is due to the result of direct compression of the spinal cord by an abscess, inflammatory granulation tissue, a dislodged sequestrum, or canal compromise due to instability. In the late stages, it is usually due to stretching of the cord over a bony ridge at the apex of the deformity (Figs. 123.13A to D and Table 123.3).

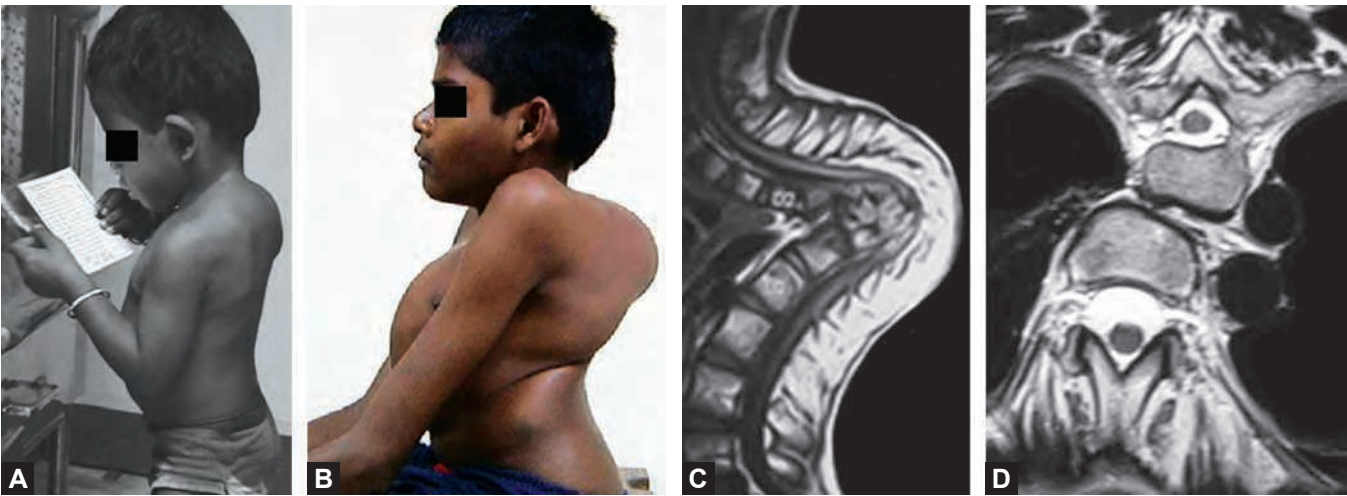
Since TB affects the vertebral bodies predominantly, the spinal cord compression starts anteriorly with a gradual

increase in the spasticity that may not be appreciated by the patient initially but evident by exaggerated reflexes and an extensor plantar response. As compression increases, the anterior and lateral columns of the cord are affected gradually leading to complete motor loss and reduction of sensations (pain, temperature, and crude touch). Later, the posterior column is also affected leading to complete loss of fine sensation and disturbances of sphincters. In long-standing compression, the spasticity is replaced by flaccidity. The neurological deficit could be categorized into the following stages⁷:

- **Stage I:** The patient does not appreciate weakness but the clinician notices clumsiness of gait and signs suggestive of cord compression.
- **Stage II:** The patient has evident motor weakness but the power is sufficient that he/she manages to walk (motor power grade 3 or above).
- **Stage III:** Bedridden (severe motor weakness) with paraplegia and sensory loss <50%.
- **Stage IV:** Complete motor weakness with loss of sensation >50% and/or bladder bowel involvement and/or flaccid paraplegia and/or paraplegia with flexor spasm.

DIFFERENTIAL DIAGNOSIS

Tuberculosis is often over-diagnosed in endemic areas and under diagnosed in developed countries. It should be differentiated from other granulomatous lesions like fungal spondylitis, metastatic and primary spinal tumors, and pyogenic spondylitis. Typical paradiscal involvement, minimal or absent clinical signs of sepsis, presence of a



Figs. 123.13A to D: Clinical photographs of a child affected by spinal tuberculosis at the age of 4 years. Though the deformity looks minimal at the completion of chemotherapy, it has significantly worsened by adolescence. Magnetic resonance imaging shows a buckling collapse with cord compression and neurological deficits. A coronal section at the apex of the deformity actually shows two vertebrae overlapping each other due to the buckling.

Table 123.3: Causes of neurological complications in spinal tuberculosis.		
Active disease		
<ul style="list-style-type: none">• Compressive pathology<ul style="list-style-type: none">– Inflammatory edema– Granulation and caseous tissue with sequestered material• Infective vasculitis• Spinal tumor syndrome• Pathological dislocation of spine• Direct infiltration of tuberculous bacilli into the cord	Usually responds well to conservative chemotherapy and a middle path regimen can safely be followed	
Healed disease		
<ul style="list-style-type: none">• Stretching of cord over the bony ridge at the apex of the deformity (internal gibbus)• Progressive constriction of cord due to extradural fibrosis	Surgery is essential to relieve mechanical compression the prognosis is guarded	

large abscess and characteristic findings on the MRI (*see below*) help to confirm the diagnosis of spinal TB.

■ INVESTIGATIONS

Laboratory Investigations

The standard blood test performed is the erythrocyte sedimentation rate (ESR). It may be markedly elevated

(>70 mm/h) and serial ESR measurements are also helpful in assessing the response to treatment. It generally normalizes within 3 months of antitubercular treatment. Failure to normalize should spur one to identify causes for the same including primary drug resistance or alternate etiology. Erythrocyte sedimentation rate, however, lacks specificity and cannot help to differentiate noninfectious causes such as malignancy. C-reactive protein (CRP) has been found to be elevated in up to 71% of patients with spinal TB.⁸ It scores slightly over ESR in that it is specific for infectious or inflammatory lesions. Changes in CRP levels take about 14 days, while ESR takes about 4 weeks to demonstrate and hence more useful in monitoring treatment response.

The role of tuberculin skin test (Mantoux) as a diagnostic tool in the present era is unclear. The tuberculin test is positive in 62–100% of patients with TB.⁹ A positive Mantoux test merely indicates cell-mediated immune response due to a previous tuberculous infection, and in endemic regions, the test can be positive even in patients without active TB. Coexistent infection by human immunodeficiency virus and other immune deficiency conditions can also give a false-negative skin test. Its diagnostic value is high in regions where TB is rare, and in endemic areas, it can at best be considered only as a corroborative evidence for TB.

Serological tests using enzyme-linked immuno assay have tested antibody response to various TB antigens, including A-60, CFP-21, ESAT-6, MPT-63, and MPT-64.

Response of IgM and IgG antibodies has also been studied. Jain et al. reported a fall of IgM titer and rise of IgG titer following 3 months of successful treatment. Though it has a high specificity, it has low sensitivity in disease endemic countries with a high infection rate. In equivocal cases of spinal infection, serologic tests for brucellosis should also be carried out in view of striking similarity in the presentation of both diseases. Serological tests for brucellosis are considered positive if the antibody titer is more than 1:80.

Polymerase chain reaction (PCR) analysis especially from tissue samples is considered very sensitive and specific for the diagnosis of spinal TB. Tuberculosis PCR from tissue aspirate has a sensitivity of 73.1%, specificity of 93.7%, and low false-positivity rates (13.6%).¹⁰ The positive agreement between histopathology (the gold standard for confirmation of diagnosis) and PCR is reported to be very good (0.69).

If TB is confirmed, the treating physician needs to perform a baseline liver function test before initiating chemotherapy. Most antitubercular drugs are potentially hepatotoxic and hence knowing the pretreatment functional status of the liver is essential.

Bacterial Culture

Bacterial culture of the infected tissue is useful to confirm the diagnosis and to acquire antibiotic sensitivities to guide therapy. Since extrapulmonary tuberculous infection is paucibacillary, it is essential to culture material from deep structures such as bone and abscess walls rather than culturing pus.

The most common solid medium is Lowenstein-Jensen (L-J), an egg-based medium. Positive detection rate with this method in spinal TB has ranged from 0% to 75%.¹¹ Though widely available, its major drawback is the prolonged time for identifying growth. Also, if a drug sensitivity report is necessary, it can be carried out only after the initial growth.

Agar media such as Selective 7H11 and liquid-based media (Becton-Dickinson and Co, BACTEC and BACTEC MGIT) now are the standard. Typical hold periods after which growth can be clearly identified are 4–6 weeks. An important use of these systems is that they allow drug susceptibility assessment. This helps in identifying drug-resistant strains and start early alternate second-line medications. This method relies on the metabolism of ¹⁴C-labeled palmitic acid leading to ¹⁴CO₂ that is quantified using specific instruments. In a comparative study, BACTEC and L-J media gave positive results of 83.87% and 61.29%,

respectively, with the average detection time being 11.3 days and 26.7 days, respectively.¹²

Histopathology and Microbiology

The confirmation of TB infection is through identification of bacillus in the tissue or by histological confirmation of typical tubercles in the infected tissue. Typically, 10^{4–6} organisms per milliliter are required in the infected tissue for detection of the bacilli. Bone tissue or abscess samples are obtained to stain for acid-fast bacilli and isolate organisms for culture and sensitivity. Acid-fast staining and culture results are positive in only about 50–60% of the cases, since skeletal TB is considered as a paucibacillary type.¹³ So, the tissue should be sent for histopathological examination. The typical histopathological findings are large caseating necrotizing granulomatous lesions with epithelioid and multinucleated giant cells with lymphocytic infiltration. The method most widely used to acquire the tissue sample is CT or fluoroscopy-guided needle/trocar biopsy. In endemic countries because of high prevalence, chemotherapy is sometimes started without a definite microbiological diagnosis. This is based on the typical clinical presentation and radiological features. However, a tissue biopsy is needed in patients with atypical findings, lack of expected response to drug therapy, suspicion of drug-resistant strains, and in patients from nonendemic places.

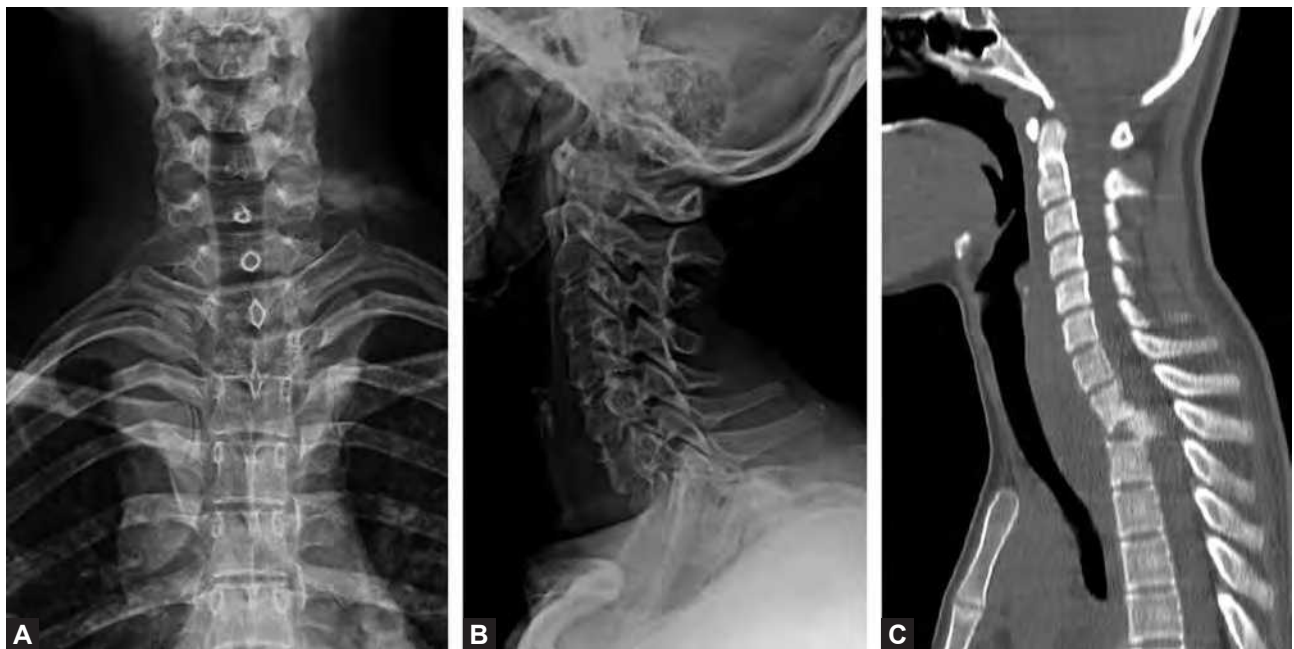
Imaging Studies

Earliest features observed on plain radiographs are vertebral osteoporosis, narrowing of the joint space, and indistinct paradiscal margin of vertebral bodies. Progressive destruction leads to vertebral collapse, kyphosis and sagittal or coronal instability. Involvement of multiple adjacent vertebra leads to wedging and a smooth, kyphotic deformity. In the cervical spine, the prevertebral soft tissue shadow can be enlarged due to distension of the abscess in the retropharyngeal region. In the thoracic spine, the cold abscess is visible on anteroposterior plain radiographs as a fusiform or globular radiodense shadow (*bird's nest appearance*) (Figs. 123.14A to C). Long-standing abscesses may produce concave erosions around the anterior surfaces of the vertebral bodies called *the aneurysmal phenomenon*.

Computed tomography and MRI can detect lesions at an earlier stage. Computed tomography is useful in assessing accurately the extent of bony destruction, early identification of posterior element involvement, and in TB of



Figs. 123.14A to C: Sagittal and coronal magnetic resonance imagings demonstrate thoracic spinal tuberculosis with perivertebral abscess formation (A and B). The anteroposterior radiograph of the thoracic spine shows the paravertebral abscess collected in the paraspinal region, indicated by yellow arrows (C).



Figs. 123.15A to C: Computed tomographic scans are quite helpful in identifying junctional “hidden” region of the spines. This patient had neck pain and neurological symptoms, and radiographs of the cervicothoracic spine shows only pedicular asymmetry on the right side in the anteroposterior view. The sagittal scan shows significant destruction of the upper thoracic vertebrae and retropulsion causing canal compromise.

Table 123.4: The different signal intensity changes in spinal cord as observed in MRI.

Cord edema: Spinal cord shows diffuse hyperintensity in T2-weighted images and diffuse hypo or isointensity in T1-weighted images.

Myelomalacia: It is considered when irregularity of the spinal cord was associated with patchy hyperintensity in T2-weighted images and hypointensity in T1-weighted images.

Cord atrophy: It is described as apparent loss of cord size with relative increase of subarachnoid space.

Syringomyelia: Dilation of central canal with change in its signal intensity as that of CSF in T1- and T2-weighted images.

Thickening to dura-arachnoid complex: It is seen as thick hypointense ring in T2-weighted images around the cord obliterating the CSF space with relative increase of subarachnoid space.

Arachnoiditis: When normal CSF signal is replaced with irregular hypointensity in both T1- and T2-weighted images.

Extradural compression

Fluid shows as diffuse hyperintensity in T2-weighted images and hypointensity in both T1- and T2-weighted images.

Caseous tissue shows mild hyperintensity in both T1- and T2-weighted images.

Granulation tissue shows heterogeneous hypointensity or hyperintensity in T2-weighted images.

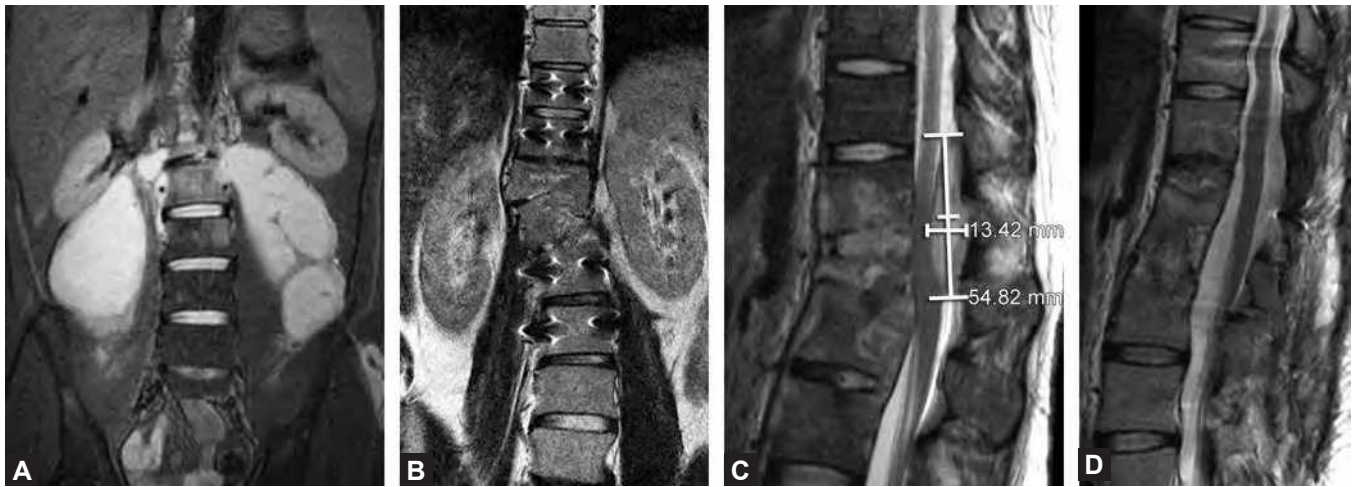
(MRI: Magnetic resonance imaging; CSF: Cerebrospinal fluid).

certain regions such as the craniovertebral and cervicodorsal junction, the sacroiliac joints, and the sacrum, which are not easily defined in the radiographs (Figs. 123.15A to C). Computed tomography is also helpful when a percutaneous biopsy is planned. *Magnetic resonance imaging* is the gold standard investigation for demonstrating the extension of disease into soft tissues and the spread of tuberculous abscess. It is the most effective method for demonstrating neural compression. Magnetic resonance imaging with contrast is also helpful in differentiating vertebral lesions from other noninfectious causes. Jain et al. have calculated the percentage canal occupancy based on CT/MRI in 15 cases of TB of spine from C3 to T12 with no neurological deficit and found that up to 75% canal occupancy by the extrinsic compressive element like abscess, sequestrum was found compatible with intact neurological state.¹⁴ However, besides cord compression, when other causative factors are added to pathogenesis of paraplegia such as vascular cause or mechanical instability, it can produce paraplegia at a lesser canal compromise (Table 123.4). It was observed that patients with relatively preserved cord size with evidence of only myelitis/edema respond well to antitubercular treatment with or without surgical decompression. Predominantly fluid collection in extradural space also resolved well with anti-tubercular treatment (ATT) alone. In patients with extradural collection with cord compression and myelitis, improvement in neural deficit was noted if surgical decompression was performed early. Patients having significant cord compression and myelomalacia did not show favorable response even after surgical decompression and had probably developed irreversible changes.

Serial MRI can be used to assess the response to treatment and regression of the disease. The healing of the vertebral lesion is diagnosed on follow-up MRI as complete resolution of marrow edema, replacement of marrow by fat seen as a bright signal on T1- and T2-weighted images, and complete resolution of paravertebral collections (Figs. 123.16A to D). However in a study by Jain et al., out of 49 patients, only 20 had complete radiological features of healing.¹⁵ So presence of residual cold abscess in the follow-up MRI despite successful chemotherapy is not an indication for surgery. *Bone scan* with Tc-99m is considered to be highly sensitive, but nonspecific. It may only aid to localize the site of active disease and to detect multilevel involvement.

TREATMENT

General supportive measures include bed rest, external bracing, nutritious diet and vitamins as required, care of bladder and bowels, and good nursing care. Modern anti-tubercular drugs are able to achieve therapeutic levels in caseous tissues and abscesses and excellent clinical cure can be achieved. Hence, uncomplicated spinal TB is considered as a medical disease with selected surgical indications. Ambulant multidrug chemotherapy is administered for all the patients, and bed rest with external bracing is advised in the initial period. The patient is followed at periodic intervals with clinical examination, radiographs, and assessment of ESR and CRP levels till complete healing is achieved. Surgical treatment is recommended for certain specific indications in these patients.



Figs. 123.16A to D: Coronal magnetic resonance imaging (MRI) of a patient with T12–L1 tuberculosis and huge abscess on the right side (A). Post-treatment MRI reveals complete resolution of abscess (B).

Antitubercular Chemotherapy

The treatment of spinal TB is primarily medical with antitubercular chemotherapy. Compliance with chemotherapy is the most important determinant of treatment outcome in spinal TB. All patients of spinal TB diagnosed before destruction has occurred (based on MRI) or patients with minimal destruction of vertebrae can be treated with chemotherapy alone. Ambulant chemotherapy, where no specific instructions for rest or activity restriction are advised, has equivalent results to institutional chemotherapy and hence preferred. Successful treatment requires the prolonged administration of antituberculous drugs (6 or 9 months). A combination of drugs is essential to prevent emergence of resistant strains. In developing countries, to ensure drug compliance, DOTS (Directly Observed Treatment Short course) has evolved. This ensures uninterrupted supply of medication and prevents the emergence of multidrug-resistant tuberculosis (MDR TB) to a large extent.

The World Health Organization guidelines for the type and duration of antituberculous chemotherapy consider spinal TB to be severe extrapulmonary (category 1) and treatment is advised for 6 months. In cases of relapse or treatment failure, treatment is prescribed according to category 2, i.e. for 9 months. The currently recommended first-line drug regime is four-drug therapy. This includes isoniazid 5 mg/kg, rifampicin 10 mg/kg, pyrazinamide 20–25 mg/kg, and ethambutol 15 mg/kg for 2 (category 1) to 3 months (if category 2) followed by isoniazid and

rifampicin for 4 (category 1) to 6 months (if category 2). In children, ethambutol is replaced by streptomycin, as it may cause optic neuritis. The British Medical Research council studies have conclusively proved that short-course chemotherapy for spinal TB is effective.¹⁶ However, their studies did not include patients with multiple vertebral involvement, cervical lesions, or those with major neurological involvement. Because of this limitation, many experts recommend 9–12 months of treatment. The exact duration of chemotherapy should be individualized. Treatment protocol of HIV-positive patients is same as of HIV negative. HIV patients with lower CD4 counts have poor prognosis.

Monitoring Treatment Response

Patients are monitored based on clinical, hematological, and radiological criteria. Usually after 8–10 weeks of starting chemotherapy, the patient begins to feel well, regains his appetite, and gains weight. The spinal pain and the muscle spasm reduce. Radiologically, the bony destruction may increase in the first 6 weeks. Thereafter, the bony destruction stops. Abscess shadow begins to decrease in size after 3–4 months and gradually regresses. The sclerosis of the bone begins by 3–4 months. At the end of 6 weeks to 2 months, the clinician is able to judge the patient's response to treatment. If a new lesion appears or the original lesion is progressing further, drug resistance should be suspected. Surgery is often necessary at this stage.

Patients are typically seen at 6-week intervals for the first 3 months and at 2-month interval till completion of

chemotherapy. The patients are monitored at intervals of 6 weeks for hepatotoxicity, optic neuritis, and renal function. Radiographs of the spine are also repeated at intervals of 6 weeks to monitor the kyphosis and the resolution of abscess shadow. At the end of 9 months of treatment, patients are assessed on clinical, radiological, and hematological grounds. The disease often becomes quiescent at this point of time. There will be no pain, muscle spasm, abscess, sinus, or neurological deficit. X-ray reveals sclerosis of the lesion. Children should be managed on the same lines as adults with appropriately adjusted doses but should be followed up to skeletal maturity as the kyphosis can deteriorate with growth.

Drug Resistance

Multidrug-resistant TB has been reported in 2.3% patients among the new cases and 17.2% among the previously treated cases. Drug-resistant TB is defined as a case of TB due to bacilli resistant to one or more antitubercular drugs. Multidrug-resistant TB is defined as disease due to *M. tuberculosis* that is resistant to isoniazid (H) and rifampicin (R) with or without resistance to other drugs. Extensively drug-resistant TB is defined as resistance to isoniazid (INH) and rifampicin along with further resistance to any fluoroquinolone and at least one injectable second-line drug.

Treatment regimens for MDR TB spine have to be tailor made according to the drug sensitivity profile of each patient. Diabetes and HIV are more frequently associated with drug resistance making treatment even more difficult.

The treatment principles for MDR TB include:

- Treatment to be supervised by qualified physicians only.
- Drug sensitivity testing should be used to guide therapy.
- Regimens should consist of a minimum of four new drugs not used previously.
- An injectable aminoglycoside should be used for a minimum period of 2 months.
- Treatment should be for a minimum duration of 24 months.

Patients on second-line drugs for resistant TB need to be monitored carefully for side effects. Complete blood counts, renal and liver function tests are performed monthly. Gastrointestinal side effects are the most common. Hepatotoxic drugs need to be stopped if the liver enzymes are five times increased from their normal values. Drug induced neuropathies can be prevented by the addition of pyridoxine to the treatment regimen from the outset.

Surgical Treatment

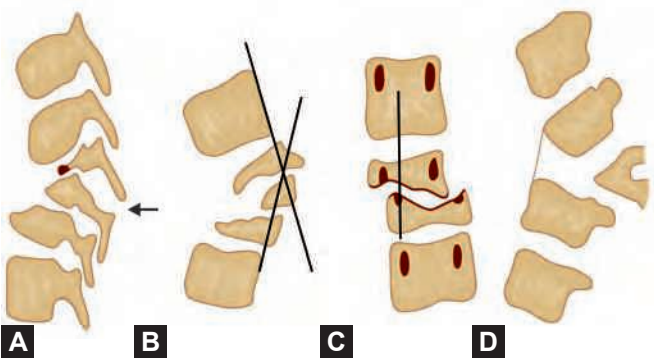
The indications for surgery in spinal TB are to obtain tissue sample for biopsy, drain an abscess cavity, decompress the spinal cord, achieve debridement of disease focus, and stabilize the spine. The evolution of surgical treatment of spinal TB has passed through different phases of development. The introduction of antitubercular drugs in the 1940s revolutionized the treatment and made surgery eminently possible.

In the pre-antitubercular era, nonoperative treatment in the form of body casts and braces invariably resulted in deformity, contractures, or death. Such disappointing results of nonoperative treatment motivated surgeons to develop surgical techniques for excision of the diseased tissue. Without chemotherapy, such procedures obviously resulted in persistent sinus and ulcer formation and death in many patients. Chipault (1896) was the first to perform laminectomy for paraplegia due to TB.¹⁷ However, the lamina was the only stabilizing structure in a spine where the anterior vertebral bodies are already destroyed. So, laminectomy procedures invariably resulted in poor results and hence the procedure was abandoned. Subsequently, anterolateral decompression through costotransversectomy approach was developed. Norman Capener (1933) is credited for the first “anterolateral decompression” procedure which he named as “lateral rhachiotomy.”¹⁸ This was performed by excising a part of the lamina and pedicle from one side to enter the spinal canal anteriorly and relieve the pressure on the spinal cord. In the absence of chemotherapy, the techniques fell into disrepute due to the high incidence of sinus formation and secondary infection. Because “direct operation on the diseased area” presented such a gloomy picture, surgeons developed “distant operations” without opening the pathological site. Albee and Hibbs (1911) introduced the posterior spinal fusion to shorten the period of immobilization.¹⁹ But as the anterior diseased tissue was not dealt with, the mycobacterium persisted with possibilities of flaring up with a drop in immunity.

The introduction of antitubercular chemotherapy achieved spectacular success in the control of disease. The availability of effective antitubercular drugs made direct surgery on the diseased area possible without dissemination of infection or sinus formation. Surgical debridement of tuberculous infection was performed through the anterior approach based on the premise that “anterior disease needs anterior surgery,” thus preserving the stable

Table 123.5: Conclusions from the different Medical Research Council (MRC) trials.

Center	Conclusions
Masan, Korea—MRC 1973	The standard drugs were potent for florid spinal tuberculosis in children and bed rest was not necessary
Pusan, Korea—MRC 1973	Streptomycin is not necessary and Plaster-of-Paris jacket offers no benefit
Bulawayo—MRC 1974	Debridement is not a good operation and clinical diagnosis assisted with radiographs was sufficient to start the treatment as was later confirmed by histopathology and/or bacteriology in 83% of patients
Hong Kong—MRC 1974	Radical anterior excision is a better operation with positive histopathology (HP) and/or bacteriology in 85% of patients
Madras—MRC 1978	Ambulatory treatment with rifampicin and isonicotinic acid hydrazide for 9 months was found to be superior to ambulatory 6 months regimen or 6 months regimen with radical resection within 1 month of start of chemotherapy



Figs. 123.17A to D: Diagram of the radiological signs for the “spine at risk.” (A) *Separation of the facet joint:* The facet joint dislocates at the level of the apex of the curve, causing instability and loss of alignment. In severe cases, the separation can occur at two levels. (B) *Posterior retropulsion:* This is identified by drawing two lines along the posterior surface of the first upper and lower normal vertebrae. The diseased segments are found to be posterior to the intersection of the lines. (C) *Lateral translation:* This is confirmed when a vertical line drawn through the middle of the pedicle of the first lower normal vertebra does not touch the pedicle of the first upper normal vertebra. (D) *Toppling sign:* In the initial stages of collapse, a line drawn along the anterior surface of the first lower normal vertebra intersects the inferior surface of the first upper normal vertebra. “Tilt” or “toppling” occurs when the line intersects higher than the middle of the anterior surface of the first normal upper vertebra.

posterior arch and ligament complex. Direct access to the anterior disease focus permitted complete clearance of the abscess, provided tissue biopsy for diagnosis and insertion of strut rib grafts to reconstitute the anterior column.

Hodgson in 1960s popularized the concept of anterior surgery with radical debridement²⁰ and placement of rib strut grafts (*The Hong Kong Surgery*), a concept originally described by Ito et al. The complications included the morbidity of anterior approach in patients who invariably had

poor pulmonary function, vascular complications, prolonged surgeries, neurological deficits, and the problems of huge anterior bone defects.²¹ Graft-related complications such as displacement, breakage, and late recurrence of a kyphus have been reported in up to 40% of patients.²²

While the morbidity of radical excision surgeries were increasingly being recognized, Tuli observed that the potential for repair and regeneration of the diseased vertebrae with multidrug combination chemotherapy was significant. Hence, surgical treatment should be reserved for select situations only (*middle path regimen*²³). The results of the series of studies by the British Medical Research Council Working Party on Tuberculosis of the Spine performed in 1965 in Korea, Zimbabwe, Hong Kong, and Madras supported this view (Table 123.5). Over time with the development of “middle path regimen,” indications for surgery have become universally more selective, less for controlling disease and more for preventing and correcting spinal deformities and neural complications and for improving the quality of function.²⁴

The natural history of progress of deformity in childhood spinal TB is different from that of adults, in that continued progression of deformity even after complete healing of disease has been observed in about 40% of children in a longitudinal study.²⁵ So it is important to identify such children at potential risk for progressive deformity during the active stages of disease, as they would benefit from early surgery. Rajasekaran evaluated the evolution of deformity in childhood spinal TB and described four “spine at risk” signs as indicators of poor prognosis for gross kyphosis mandating surgical treatment²⁶ (Figs. 123.17A to D). The loss of integrity of the facet joints was the common determining factor in all the four signs. These

Table 123.6: Indications for surgery in spinal tuberculosis.

Neurologic deficit
Severe neurological deficits at presentation
Rapidly worsening deficits
New onset or deteriorating deficits during chemotherapy
Unimproved deficits after 6–8 weeks of chemotherapy
Spinal instability
Panvertebral disease
>3 contiguous vertebra involved
Vertebral body loss >1 in thoracic spine and 1.5 in lumbar spine
Children with initial kyphosis >30°
Children with “spine at risk” signs
Posterior neural arch with pedicular destruction
Clinical instability
Late deformity
Severe kyphosis with late onset neurological deficits
Lack of clinical response to chemotherapy
Failure of clinical improvement after 6 weeks of chemotherapy
Disease recurrence despite chemotherapy
Primary drug resistance

signs appear early in the course of the disease at which time it is much easier to do a prophylactic surgical fusion and column reconstruction. Such prophylactic surgery would be useful to prevent late complications like “buckling collapse” and late onset paraplegia.

Different Surgical Techniques

Currently, surgery in spinal TB is performed to achieve any or all of the following aims:

- Debridement and drainage of large cold abscesses
- Decompression of spinal cord and neural structures
- Spinal deformity correction using spinal instrumentation
- Reconstruction of the anterior column
- Stabilization of the spine with anterior and/or posterior instrumentation.

These goals can be achieved through different surgical approaches and decided on an individual basis (Table 123.6). The different surgical techniques can be grouped under the following approaches:

1. *Anterior decompression and reconstruction through an anterior approach:* The vertebral body reconstruction may be performed using a variety of grafts such as ribs, iliac crest, fibular graft, or even allografts. In the

last few years, reconstruction by titanium cages is used very successfully. Stabilization is achieved by anterior instrumentation, either plates or rod systems. The limitations of anterior approach include poor access to the upper thoracic spine, lower lumbar and lumbosacral spine, working around a diseased lung, risk of injury to viscera, vascular structures, sympathetic chain and thoracic duct, inadequate deformity correction, and a higher morbidity of the approach. A combined anterior plus posterior procedure helps overcome some of the instrumentation-related drawbacks of the isolated anterior operation. However, it entails two operations with associated additional morbidity.

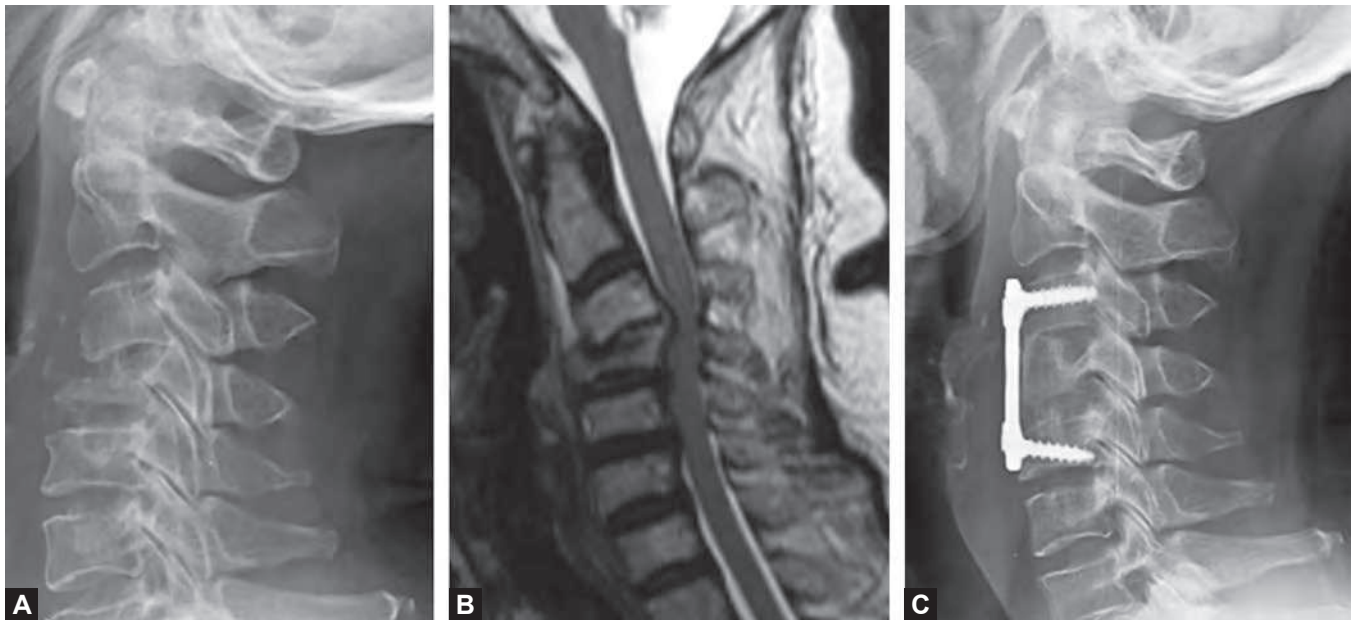
2. Posterior instrumentation and anterior decompression performed through two separate approaches in single or two stages. This is indicated in patients with significant vertebral destruction and kyphosis, where anterior decompression with reconstruction of the anterior column and posterior stabilization are mandatory.
3. An “all posterior approach” is becoming increasingly popular. The decompression, reconstruction of the anterior column, and instrumentation are all achieved from the posterior approach. Anterior reconstruction of vertebral defects up to one vertebral level can also be performed through a transpedicular or anterolateral route through the posterior approach.

The availability of pedicle screw systems that provide excellent reconstruction possibilities along with the development of surgical techniques that allow anterior reconstruction through a posterior approach have tilted the balance in favor of posterior surgeries in spinal TB. The safety of use of titanium pedicle screw system even in the presence of abscess has enabled the extensive use of this system even in active spinal TB. Though there was initial apprehension to use metal implants in active infection, it was proven by Oga et al. that the tubercle bacilli unlike pyogenic organisms does not adhere to metal and form any biofilm.²⁷

Surgical Techniques

Anterior Techniques

The most common region of the spine involved in TB is the vertebral body. Therefore, it is logical that an anterior surgery to decompress and reconstruct the spine would be the ideal approach. Anterior surgery offers the advantage of direct access to the diseased region, visualization of neural structures while debridement and decompression,



Figs. 123.18A to C: Lateral radiograph and sagittal magnetic resonance imaging show C4 vertebral body tuberculosis with kyphosis causing cord compression (A and B). The lesion has been treated by anterior debridement, iliac crest autograft reconstruction, and stabilization with a plate (C).

and the ability to insert strut grafts in the space created after debridement. Anterior decompression surgeries performed in the 1980s involved radical removal of the entire vertebrae that were involved. We now know that removal of the infected foci up to bleeding normal bone is sufficient, as the chemotherapy is efficient in clearing the residual infection. The use of a cage and bone grafts allows for more secure, accurate, and dependable deformity correction. The cage provides a more rigid fixation construct and minimizes the risk of graft subsidence or dislodgement.

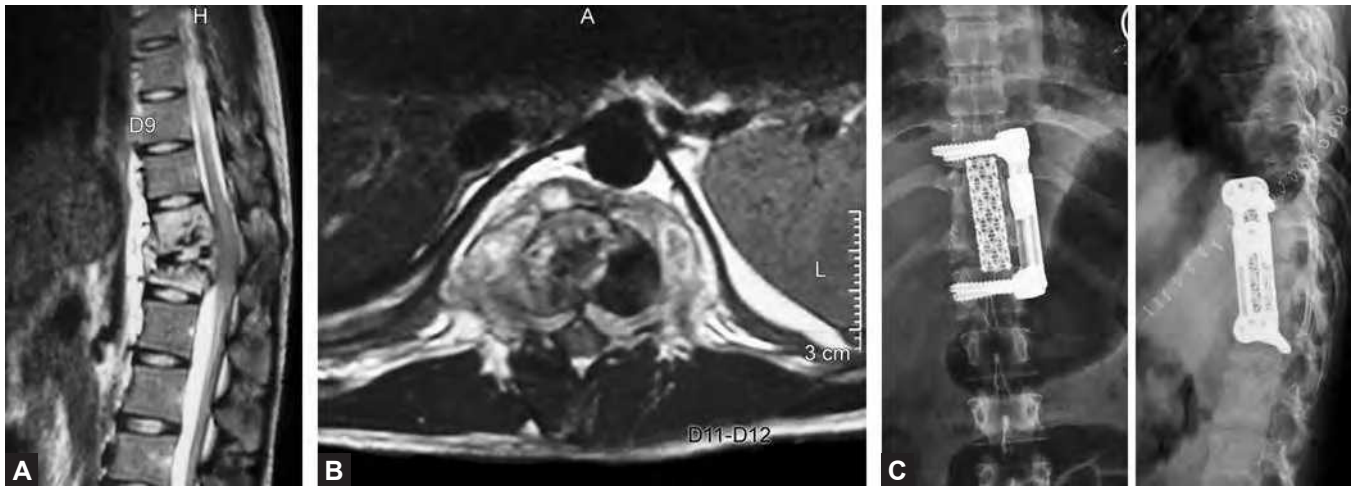
Current standard practice is to use either cages with bone grafts or structural allografts supplemented with anterior or posterior instrumentation. The commonly used anterior instrumentation is screws placed in the vertebral body connected through rods. Single screw rod suffices in most patients but double screws may need to be inserted, if the kyphosis corrected has been significant or the vertebral dimensions are wide.

The standard surgical approach for the subaxial cervical spine is the anterior decompression and reconstruction. Posterior techniques are not used in cervical spine as they impede any anterior decompression, provide only weak bone anchors and the comparative ease of anterior surgery in the cervical spine. The anterior approach to the cervi-

cal spine exposes the anterior vertebral bodies from C3 to T1 (Figs. 123.18A to C). It is used for debridement and reconstruction, biopsy of vertebral bodies and disc spaces and drainage of abscesses. If the level of pathology is localized, a transverse skin crease incision is made at the appropriate level of the vertebral pathology.

Technique—Cervical Spine

The incision should extend obliquely from the midline to the posterior border of the sternocleidomastoid muscle. The fascial sheath over the platysma is incised in line with the skin wound using the fingers, gently retracting the sternocleidomastoid muscle laterally. A plane is developed between the medial edge of the carotid sheath and the midline structures (thyroid gland, trachea, and esophagus), cutting through the pretracheal fascia on the medial side of the carotid sheath. The sheath and its enclosed structures laterally with the sternocleidomastoid muscle are retracted. Occasionally, either or both of the thyroid arteries that connect the carotid with the medial structures may have to be divided to open the plane. After splitting the pretracheal fascia by blunt dissection the cervical vertebrae are visualized, covered by the longus colli muscle and the prevertebral fascia. Once the prevertebral fascia is



Figs. 123.19A to C: Magnetic resonance imaging of a patient with back pain shows destruction at D11–12 levels with abscess formation and kyphosis. Anterior reconstruction at the dorsolumbar junction has been performed using mesh cage and dual screw vertebral fixation.

incised, the abscess collected beneath it is let out completely. The longus colli muscles are held retracted on either side by self-retaining retractors. Thorough debridement of the necrotic tissue is done with curettes, high speed burr, and rongeurs. In case of corpectomy, the discs on either side are removed first followed by removal of the body. It is ensured that the spinal cord is decompressed adequately. An appropriate sized cage or allograft is tapped into place and secured with plates and screws.

Technique—Thoracic and Thoracolumbar Spine

In the thoracic spine, the affected vertebral body is reached through a standard thoracotomy. Either extrapleural or transpleural dissection is performed to access the vertebral body. Once the affected vertebral region is reached, the prevertebral fascia is incised to let out the tuberculous abscess. The segmental vessels over the affected vertebral bodies are ligated. The discs above and below the infected body is excised first. The necrotic bone tissue is removed by a combination of osteotome, nibbler, and high speed burr. The posterior vertebral cortex and the epidural granulation tissue are removed at the last. This prevents the dura from bulging inside the field during vertebral resection. After appropriate debridement, the defect is reconstructed with a cage or a structural allograft and supplemented with anterior stabilization (Figs. 123.19A to C).

Posterior Techniques

The advantages of the posterior approach include:

- Surgeon is familiar with the approach.
- Excellent exposure for circumferential spinal cord decompression.
- Instrumentation can be easily extended for multiple levels.
- Posterior instrumentation is stronger and allows better control of deformity correction
- Depending upon the approach, anterior reconstruction can be safely performed in addition to the posterior procedure.
- All the posterior approaches are extrapleural and hence preferred in patients with TB, where lung function may be poor and the lung may be adherent to the chest wall.

Posterior/posterolateral approaches can broadly be grouped into the following:

- Laminectomy
- Transpedicular
- Costotransversectomy
- Lateral extracavitary

Laminectomy

In the thoracic spine, a laminectomy alone offers exposure of the posterior epidural space only. It does not allow decompression anterior or anterolateral to the spinal cord.

Also, in patients with anterior vertebral involvement, a laminectomy creates a globally unstable situation that may potentiate instability and progressive kyphosis. Hence, it is useful and advocated only rarely when the vertebral body is unaffected but there is a posterior epidural mass compressing the spinal cord that needs to be excised.

Transpedicular Approach

The transpedicular approach serves as an excellent portal for debridement of the vertebral body and decompression of the spinal cord. A unilateral transpedicular approach offers >180° exposure of the spinal cord from midline posteriorly to slightly beyond the midline anteriorly, while a bilateral transpedicular approach would allow a circumferential decompression of the neural elements. Although cancellous chip grafts and cages up to 15–20 mm can be packed anteriorly, insertion of large strut grafts/cages >20 mm via the transpedicular approach is difficult due to the intact ribs (thoracic spine) and paraspinal musculature. Hence, this approach is not recommended when there is significant destruction of the vertebral body that requires reconstruction of the anterior column. A transpedicular approach is useful in patients where the primary problem is a neurologic deficit secondary to anterior or lateral compression of the spinal cord and when the structural integrity of the vertebral body is intact with only a minimal kyphotic deformity. However, adequate extent of fixation is mandatory to avoid implant-related complications (Figs. 123.20A and B).

The transpedicular approach utilizes the pedicle as a channel for entry anteriorly into the vertebral body and the adjacent disc for debridement of the infected focus. A posterior midline incision is taken. The muscles are dissected subperiosteally to the tip of the transverse processes. Pedicle screws are inserted cephalad and caudad to the diseased level and a rod is inserted on the side contralateral to the planned transpedicular approach. At the diseased level, adequate laminectomy is performed to relieve cord compression. The transpedicular approach is then started by using a pedicle probe and creating a tract across the pedicle into the vertebral body. A tap or a high speed drill is now used to widen the pedicle canal. The transverse process is resected at its base. If there is a large prevertebral abscess, the author prefers to gently dislocate the costotransverse joint with a Cobb elevator in order to drain the abscess. The lateral wall of the pedicle is now resected to allow more medial angulation for debridement of the vertebral bodies and the intervening disc. Once

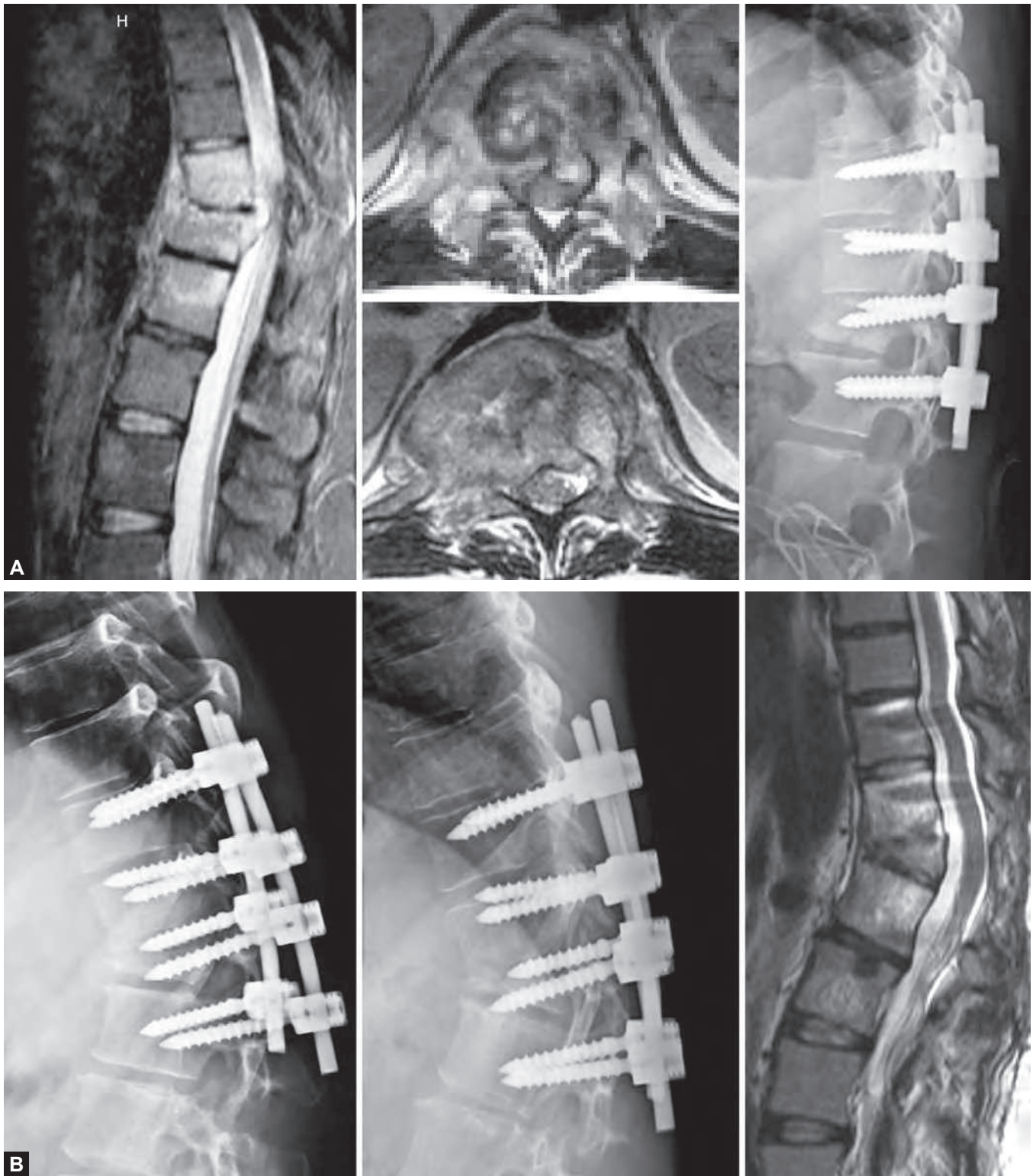
the desired amount of debridement is achieved, then the medial pedicle wall is excised so as to access the anterior epidural space. The middle column consisting of the posterior wall of the vertebra along with the mass of epidural granulation tissue is then excised to decompress the neural elements. In patients with significant destruction of the vertebral body, a thorough anterior debridement through a bilateral transpedicular approach and shortening of the spine by applying compression across the diseased segment using the posterior pedicle screws and rods can be performed (Figs. 123.21A to F). Decortication is then done and bone graft laid over the decorticated surfaces for good fusion. A cross-link can be used if additional stability is necessary.

Costotransversectomy

The costotransversectomy approach was originally described for drainage of a prevertebral abscess secondary to thoracic TB. It involves excision of the medial 4 cm of the rib along with the rib head to gain a more oblique access anteriorly into the vertebral body. Since there is more room posterolaterally, a strut graft can be delivered into an anterior intervertebral defect and manipulated into position without having to retract the spinal cord. This approach is useful in patients where the disease is restricted to one or two levels (Figs. 123.22A to C).

The operation may be performed in the prone or lateral decubitus. Skin incisions described for this approach include longitudinal midline or paramedian, semicircular, oblique along the rib to be excised, or a T-shaped incision. With a T-shaped incision, where the horizontal component of the “T” is placed longitudinally along the midline and the vertical component placed transversely along the ribs, this approach can be used to perform circumferential decompression of the cord and simultaneous stabilization of the anterior and posterior columns. The authors prefer the midline longitudinal incision in the prone position. The paraspinal muscles are dissected from the midline subperiosteally and retracted to the tip of the transverse process. The paraspinal muscles are then divided horizontally at the level of the pathological vertebra to extend the lateral exposure. Posterior instrumentation is placed at the levels cephalad and caudad to the pathology, and a temporary rod is assembled on the contralateral side.

The medial 5 cm of the rib to be resected is exposed subperiosteally while preserving the intercostals neurovascular bundle. The costotransverse ligaments are cut and the rib is divided laterally at its posterior angle.



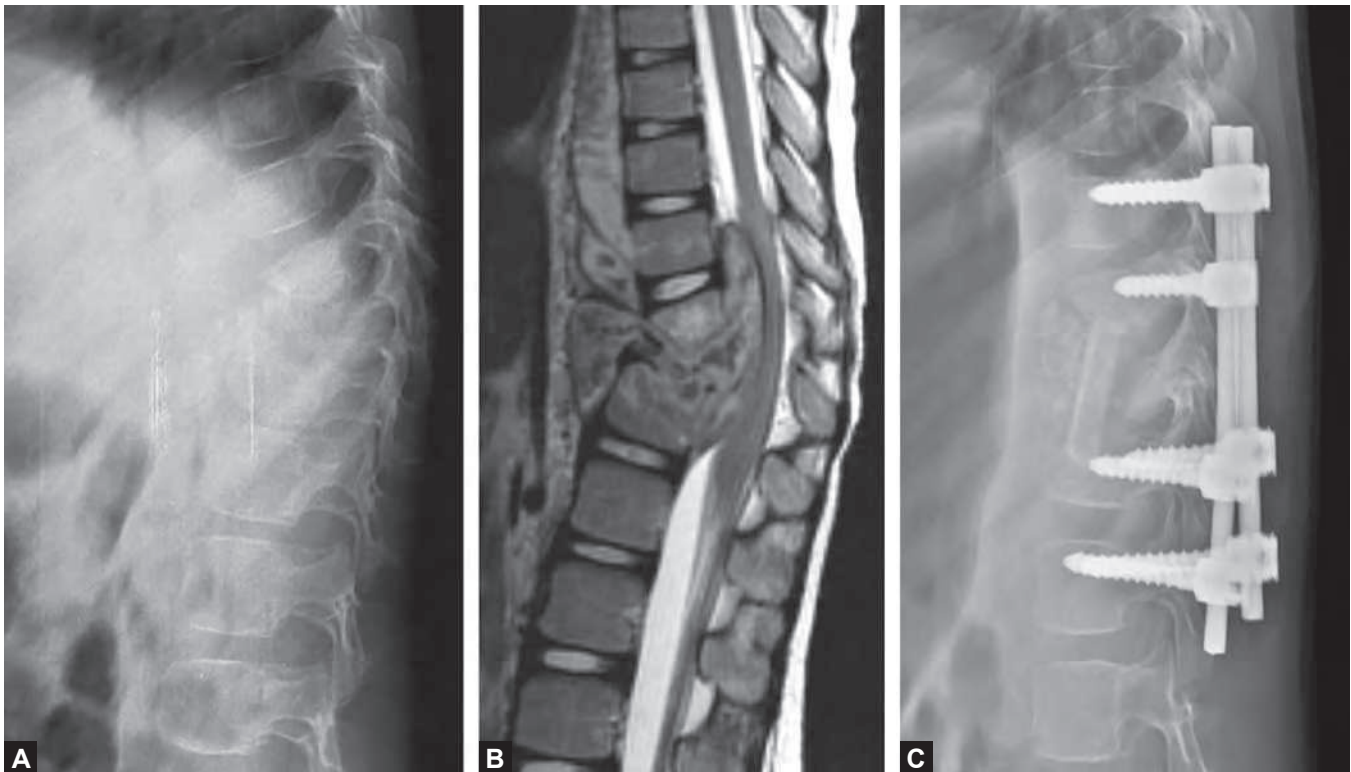
Figs. 123.20A and B: Posterior fixations for the treatment of tuberculosis should include at least two normal vertebral segments above and below the diseased segments. In this patient with T9–11 tuberculosis, four contiguous segments have been stabilized. In the follow-up radiographs, it is noted that the affected vertebra has collapsed leading to local kyphosis and implant pullout at the caudal fixation. The deformity did not progress further and healing occurred with complete resolution of the abscess.



Figs. 123.21A to F: (A and B) T2 sagittal and axial MR images of a 44-year-old patient showing spondylodiscitis involving the T6-T7 vertebra. The epidural abscess is causing cord compression. (C and D) AP and lateral radiographs of the same patient showing collapse of disc space and anterior vertebral erosion. (E and F) Postoperative lateral and AP radiographs show posterior stabilization involving two-adjacent segments. Posterior laminectomy and transpedicular decompression has been performed.

The transverse process too is cut at its base exposing the lateral surface of the pedicle. The rib is then followed up to its articulation with the vertebral body and disarticulated from the vertebral body. Excision of the rib opens up the

prevertebral abscess. More than one rib can be excised to offer a wider longitudinal exposure. The endothoracic fascia along with the parietal pleura is dissected off the vertebral body and pushed anteriorly exposing the lateral



Figs. 123.22A to C: Thoracolumbar tuberculosis in a child with destruction of multiple thoracic vertebrae T9–T10 (lateral radiograph—A). There is a huge prevertebral and epidural abscess causing cord compression in the sagittal magnetic resonance imaging. The lesion has been treated by a single stage, anterior debridement with fibular strut graft reconstruction, and posterior pedicle screw stabilization through a posterior approach.

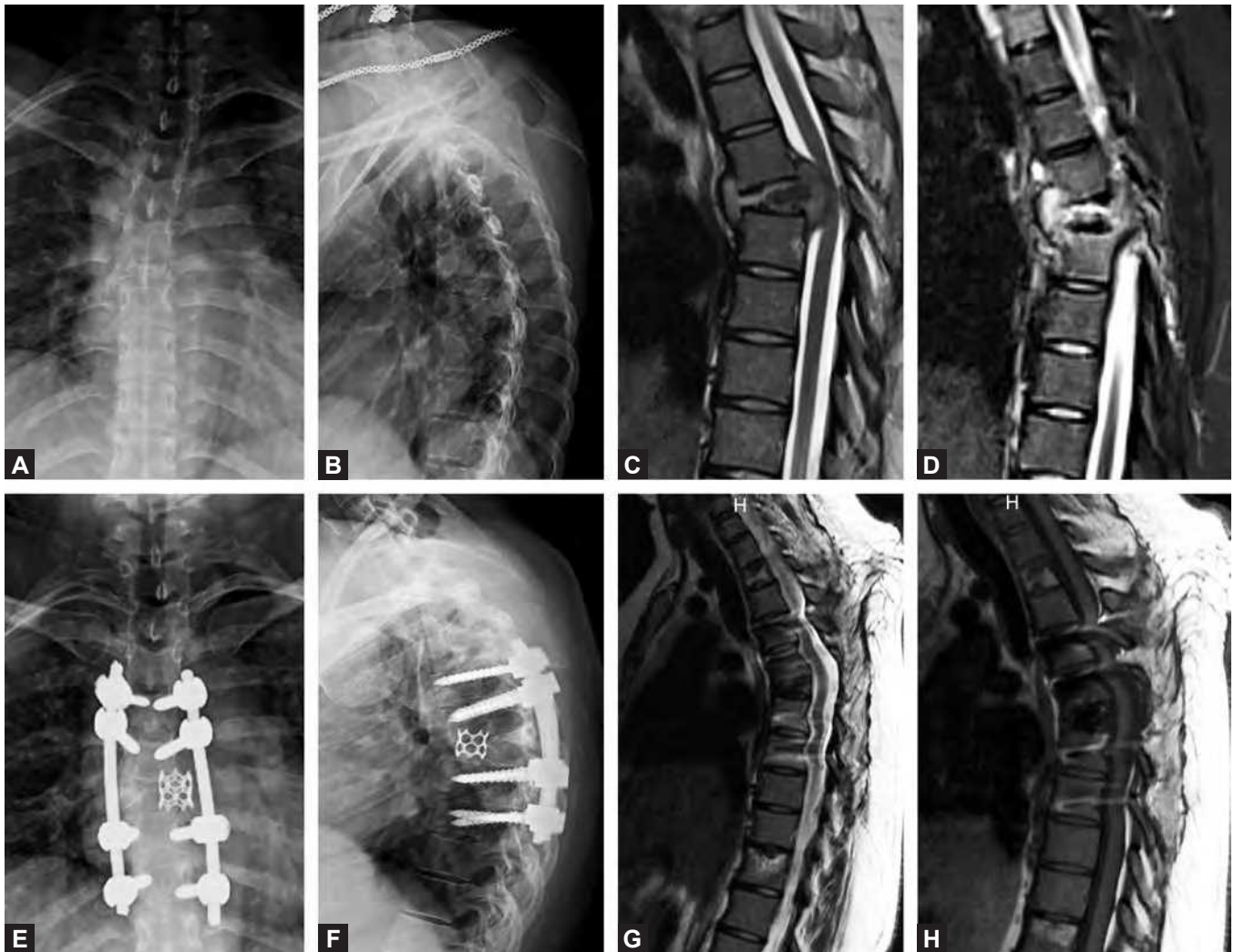
part of the vertebral body. The intercostal vessels can be ligated and the intercostal nerve is traced back to the neural foramina. The ipsilateral lamina, facet joint, and pedicle are now excised at one or more levels. This allows access for decompression of the spinal cord posteriorly, laterally, and anteriorly. Debridement of the anterior vertebral body is then performed following which anterior strut graft or cage can be wedged into the anterior defect. Posterior rods are assembled and compression applied across the diseased segment to load the graft and hold it firmly in position. Decortication of the posterior elements is performed along with a posterior and intertransverse fusion.

Lateral Extracavitary Approach

The lateral extracavitary approach is essentially a lateral extension of a costotransversectomy. The more extensive rib resection provides a wider view of the anterior structures across the midline. This approach can be utilized both in the thoracic and lumbar spine. It is easier to perform in

the thoracic spine where the anterolateral surface of the vertebra is devoid of any musculature (Figs. 123.23A to H). Also the intercostal nerves can be sacrificed for improved exposure. In the thoracolumbar and lumbar spine, the muscles (including the diaphragm at L1) originating from the anterior and lateral surface of the vertebral body require to be dissected to get an adequate anterior exposure. Besides the lumbar nerves lying within the psoas muscles need to be handled carefully to prevent a post-operative neurological deficit.

In the prone position, a midline vertical incision is made that extends three levels above and below the pathological level. The lower part of the incision is gently curved laterally for about 5–6 in. The skin, subcutaneous tissue, the thoracolumbar fascia, and the trapezius or the latissimus dorsi are lifted up as a flap from the midline along the line of the incision. The flap is retracted laterally. A plane is defined along the lateral aspect of the erector spina muscles from where the muscles are elevated as a layer off the ribs and retracted medially. On the opposite side, the



Figs. 123.23A to H: All posterior global reconstructions of thoracic tubercular spondylitis. The patient has complete destruction of T6 vertebral body with epidural abscess and neurological deficit. He has been treated by posterior stabilization, decompression and anterior vertebral reconstruction with a cage.

spine is exposed to the tip of the transverse processes in the standard fashion. Posterior pedicle screws are inserted bilaterally as required. A rod is inserted into the screws on the contralateral side. On the ipsilateral side, the ribs are then dissected subperiosteally and divided at a distance of 10 cm from the costotransverse joint. The transverse process is excised at its base and the rib is dissected off the vertebral body and excised. Usually two to three ribs are excised to obtain an adequate exposure along the length of the anterior column. The endothoracic fascia along with the parietal pleura is then dissected off the vertebral body and pushed anteriorly. The segmental vessels are dissected off the vertebral bodies and divided after ligating them. The intercostal nerve is traced back toward the dura and the

nerve roots are ligated proximal to the dorsal root ganglion and divided. The pedicles along with the ipsilateral laminae and facets are excised so as to visualize the posterior, lateral, and anterior part of the spinal cord. The entire lateral surface and part of the anterior surface of the vertebra is visible. For performing a corpectomy, the disc above and below is identified and excised. The vertebra is then resected from laterally across leaving behind a thin shell of bone anteriorly and posteriorly. Then the entire posterior shell is pushed forward anteriorly before excising it.

The vertebral end plates are then prepared. An adequate size graft/cage is then wedged into the anterior defect about 1 cm anterior to the dural sac. The second posterior rod is then assembled and compression is applied across

the diseased segments in order to firmly hold the graft in position.

Transforaminal Approach

Posterior approaches have a more limited role in the lumbar spine because it is difficult to dissect the iliopsoas muscles from the lumbar vertebral bodies; the lumbar roots cannot be sacrificed making it difficult to perform complete vertebral body excision and reconstruction; and combined anterior with posterior surgery is preferred to a long posterior fixation to preserve lumbar motion segments.

Most commonly posterior surgery is limited to fixation for providing additional stability to the anterior construct. Another indication where the posterior approach finds a role in the lumbar spine is when the disease involves the peridiscal region of adjacent vertebral bodies resulting in severe pain, focal kyphosis, instability, or a neurologic deficit. Here, a PLIF (posterior lumbar interbody fusion) or a TLIF (transforaminal lumbar interbody fusion) like procedure has been used with great success. Indications for TLIF include the presence of localized kyphosis, presence of significant radiculopathy or neurologic deficit, or worsening of radiculopathy or neurologic deficit during ongoing chemotherapy resulting from presence of dural compression by diseased tissue.

A posterior midline approach is performed in the prone position. Pedicle screws are inserted at the involved levels or the adjacent vertebral body in case the amount of destruction at the involved level is excessive. The screws are fixed to a contoured rod on one side (lesser involved side neurologically and radiologically) with distraction at the involved segment. Psoas abscesses can be drained through the intertransverse window if required. Decompression of the neural elements is performed through a laminectomy. Epidural granulation and diseased tissue within the disc space is thoroughly excised. The anterior third of the disc space is packed with morselized bone graft, and an adequately sized interbody cage packed with bone is introduced. In some patients, only a cancellous autograft was used to fill the interbody gap. Pedicle screws on both sides are then fixed to precontoured rods under compression.

SURGERY IN HEALED TUBERCULOSIS

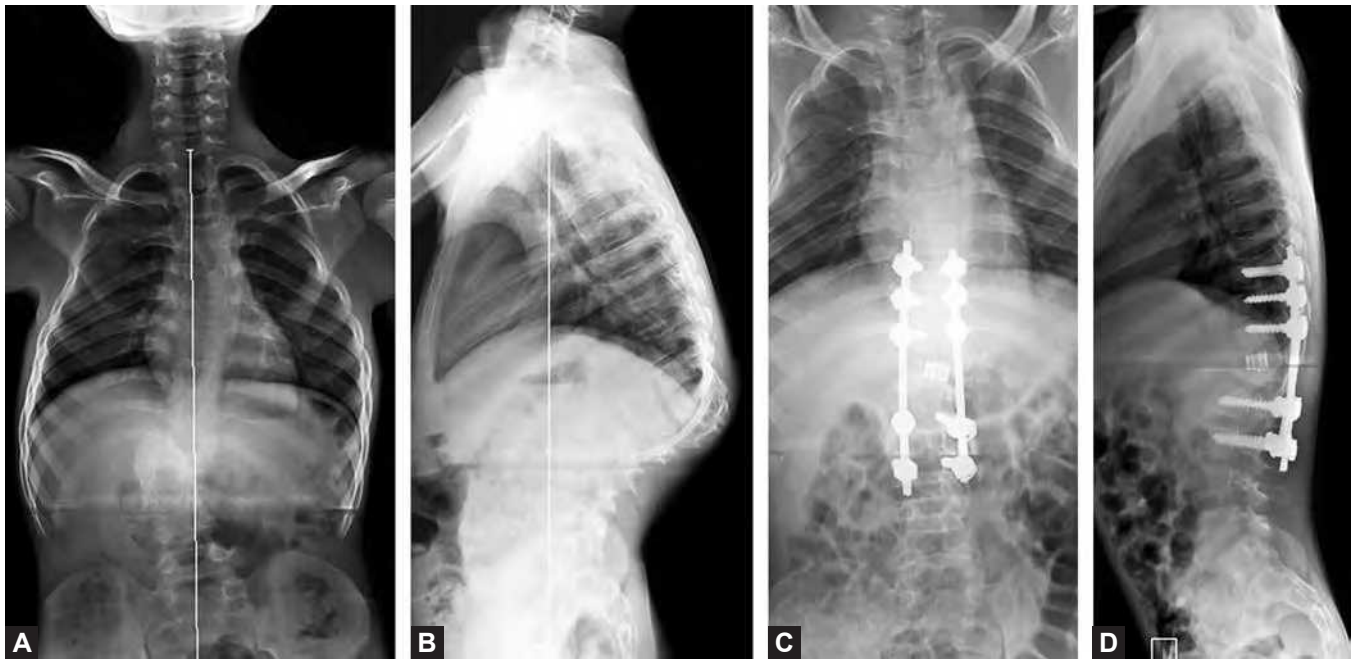
Modern antituberculous drugs have enabled a high rate of disease cure in spinal TB with good healing of the

lesion. Advances in imaging studies have helped to diagnose spinal TB in predestructive or early destructive phase obviating the need for surgery in many cases. Hence, most patients with healed TB are asymptomatic. Though complete cure may be achieved with chemotherapy, 3–5% of the patients end up with a deformity of $>60^\circ$.²⁸ The basic pathology in most patients with symptomatic healed disease is the development of kyphosis. Depending on the severity of deformity, the patient can present with persistent localized pain, costopelvic impingement, secondary cardiorespiratory problems, and late onset neurological deficits. Management of established kyphotic deformities can be difficult and fraught with complications.

Anterior, combined anterior and posterior, and posterior alone procedures have been described for the correction of established deformities, each having their own advantages and disadvantages. Anterior alone procedures have been reported for the correction of deformities in spinal TB. Adequate canal decompression, good correction of the deformity, and stabilization of the spine are the potential advantages. But such procedures are associated with difficulties in approaching the concavity of the angular kyphosis in deformities of $>60^\circ$ and hence did not gain popularity.

Kyphus correction surgery through combined approaches involves anterior corpectomy to achieve decompression, shortening of the posterior column, posterior instrumentation, and anterior and posterior bone grafting. Compared with other kinds of decompression techniques, anterior decompression has several advantages like direct access to the apex of the kyphosis, direct observation of tension of spinal cord at the time of correction of kyphosis, controlled decompression of the spinal cord, and it allows anterior strut graft fusion to stabilize the kyphosis. Posterior osteotomy can bring better correction of kyphosis, and combined anterior and posterior instrumented fusion can improve the rate of fusion. However, the disadvantage of the anterior-posterior procedure is the need for two surgical approaches to treat one pathology, resulting in increased blood loss, higher rates of infection, and prolonged surgical time.

The development of osteotomy techniques has advanced our ability to treat spinal deformities. The benefits of these techniques are that significant correction can be achieved at a single level. On the other hand, these techniques are often associated with significant bleeding, increased risk for neural injury, and are technically demanding to perform.



Figs. 123.24A to D: Posterior closing-opening wedge osteotomy to correct a post-tubercular kyphotic deformity. (A and B) Preoperative anteroposterior (AP) and lateral radiograph of the patient shows a kyphotic deformity of 118° at the thoracolumbar junction between T9 and L3 vertebrae. (C and D) Postoperative AP and lateral radiograph shows good correction of the deformity with pedicle screw instrumentation placed at least three levels proximal and distal to the apex. The “opened” anterior wedge has been reconstructed with a titanium mesh cage.

Posterior-only procedures for the correction of post-infection kyphotic deformities include transpedicular decancellation procedures, pedicle subtraction osteotomy, posterior vertebral column resection, and closing-opening wedge osteotomy. Deformities of smaller magnitude are corrected by decancellation procedures or pedicle subtraction osteotomy. More complex deformities require vertebral column resection procedures. The authors prefer a single-stage closing-opening wedge osteotomy to correct post-tubercular deformity of $>60^\circ$ (Figs. 123.24A to D). In a series of 17 patients who underwent this surgery, the average preoperative kyphosis improved from $69.2^\circ \pm 25.1^\circ$ to $32.4^\circ \pm 19.5^\circ$ postoperatively. The percentage correction of kyphosis achieved was $56.8 \pm 14.6\%$ (range 32–83%). The authors concluded that this technique is an effective method to correct severe post-tubercular kyphosis (PTK) with the advantage of being a posterior-only single-stage correction allowing for significant correction with minimal complications.²⁹

CONCLUSION

The poor outcome of TB of the spine that was once dreaded in the prechemotherapy era has improved significantly

after the availability of antitubercular drugs. The invention of modern diagnostic aids such as MRI and advances in the safety and execution of spine surgery has significantly changed the prognosis of these patients. Magnetic resonance imaging allows the diagnosis of a tuberculous lesion, with a sensitivity of 100% and specificity of 88%, well before deformity develops. Neurological deficit and deformity are the worst complications of spinal TB and are now detected much earlier than before. However, the present-day physicians are faced with newer problems of TB such as atypical clinical presentations, changing patient profile from lower strata to the higher social class, drug resistance, and the combination of HIV with TB infection. Surgeons should be aware of these pitfalls and provide the best care to the affected individual. It is important to reiterate that TB of the spine without complications is a medical disease and surgery is required to prevent and treat complications of deformity progression or neurological deficit. Panvertebral lesions, therapeutically refractory disease, risk or presence of severe deformity, a severe or progressively worsening neurological deficit, and lack of improvement or deterioration despite adequate chemotherapy are indications for surgery.

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SECTION

14

Complications

Marcel F Dvorak

Medical Complications in the Adult Spinal Patient

Daniel A Baluch, Ngoc-Lam Nguyen, Alpesh A Patel

Snapshot

- » Pulmonary Complications
- » Cardiac Complications
- » Venous Thromboembolism
- » Delirium

INTRODUCTION

Complications are an inherent aspect of surgery. Adverse events such as wound infection, instrumentation failure, and pseudarthrosis are frequently encountered by spine surgeons and are replete in the literature. However, medical complications, although widely prevalent in the surgical patient, are frequently beyond the spine surgeon's expertise and far less reported.

Medical comorbidities have substantial influences on the spinal surgeon's decision making as well as on the patient's clinical result. As the population continues to age, more and more elderly patients will be presenting for the evaluation of spinal pathology, as will the number of comorbidities affecting them.^{1,2} In patients >65 years of age, lumbar spinal stenosis is the most common indication for spine surgery.² Several studies have demonstrated that, in this patient cohort, comorbidities such as cardiovascular disease, lower extremity arthritis, and self-reported poor health are powerful predictors of inferior surgical outcome and increased complication rates in those undergoing decompression procedures.^{1,3,4}

According to *Taber's Cyclopedic Medical Dictionary*, a complication is "an added difficulty; a complex state; a disease or accident superimposed on another without being specifically related, yet affecting or modifying the prognosis of the original disease."⁵ Whereas surgical complications are ones that can be directly attributable to the operative procedure, medical complications in the surgical

patient are those that cause an increased burden on the patient's health yet are not caused directly by the operation. Having an understanding of common comorbidities that afflict the adult spinal patient is critical in order to maximize the chance of a successful operation while mitigating the risk of morbidity and mortality in the perioperative period. This chapter will discuss the prevention, diagnosis, and initial management of several of the most frequent medical complications in the adult spinal patient.

PULMONARY COMPLICATIONS

At 13%, pulmonary complications are the most frequently encountered medical issues following spine surgery and are associated with a 10-fold increased risk of death within 2 years.⁶ Both patient and surgical factors such as age, comorbidities, smoking history, increasing surgical invasiveness, and transthoracic approaches all significantly increase the risk of pulmonary complications and should be addressed and discussed with the patient preoperatively.^{6,7}

Pneumonia, which occurs in roughly 5% of all spinal surgery patients, has been reported as the leading cause of major medical complications in patients age 65 and older and is responsible for the majority of pulmonary complications.^{6,8} The clinical diagnosis is made in the patient with fever, productive cough, dyspnea, leukocytosis, and consolidation on chest X-ray and is confirmed with Gram stain and sputum culture. Nosocomial pneumonia is frequently the cause in postoperative patients and the predominant

pathogens include gram-negative bacilli and *Staphylococcus aureus*.⁹ Empiric antibiotics can be initiated once a specimen is obtained and tailored appropriately as organisms are identified.

Risk factors for postoperative nosocomial pneumonia include age > 70, pulmonary disease, smoking history, malnutrition, increased duration of surgery, thoracic/anterior approaches, and immobilization.¹⁰ As such, smoking cessation and nutritional optimization should be discussed with the patient well before the operation. Postoperatively, adequate analgesia is paramount to reduce chest splinting and promote aggressive pulmonary toilet. Early and frequent mobilization and physiotherapy focused on deep breathing are other important prophylactic measures.

Although less common, acute lung injury (ALI)/acute respiratory distress syndrome (ARDS) is a continuum of a more severe pulmonary complication. Occurring after 1.3% of spine surgeries, this condition is characterized by an acute onset of severe hypoxemia recalcitrant to oxygen therapy with bilateral pulmonary infiltrates.⁶ Noncardiogenic pulmonary edema leads to diffuse alveolar damage secondary to etiologies such as pneumonia, sepsis, shock, trauma, and transfusion-related acute lung injury (TRALI).¹¹ The distinction between ALI and ARDS is strictly based on a P_aO_2/F_iO_2 ratio of ≤ 300 mm Hg and ≤ 200 mm Hg, respectively; however, clinically, patients with ARDS are much more in extremis.¹² Although multiple treatment strategies have been proposed, management is primarily supportive via mechanical ventilation.¹³

Among adult patients undergoing spine surgery, those having reconstructive procedures for deformity have substantial risks for developing ALI and respiratory failure. Urban et al. revealed that 8 of 55 patients (14.5%) who underwent sequential anterior-posterior deformity correction developed noncardiogenic pulmonary edema and elevated pulmonary vascular resistance.¹⁴ In a subsequent study using bronchoalveolar lavage (BAL) during spinal deformity surgery, the authors demonstrated significant increases in inflammatory cells and cytokines interleukin-6 and tumor necrosis factor alpha that correlated positively with ventilatory requirement. There was also a significant correlation between the number of inflammatory cells, namely lipid-laden macrophages, in the BAL and the number of vertebral segments fused.¹⁵ These data suggest that increasing invasiveness as seen in deformity surgery may lead to a showering of the pulmonary vasculature with inflammatory mediators that promotes microvascular permeability responsible for diffuse alveolar injury and

subsequent respiratory failure. As such, those undergoing complex, multilevel spine surgery must be monitored closely for any evidence of respiratory compromise.

CARDIAC COMPLICATIONS

Among the most serious adverse medical events that can occur in the perioperative period, cardiac complications are associated with substantial morbidity and mortality. According to a retrospective analysis of 1,591 patients, those with cardiac complications following spine surgery had a greater than fourfold increased risk of death within 2 years of the operation. This study also identified an overall 8.4% incidence of cardiac complications, with arrhythmia and myocardial infarction (MI) or ischemia being among the most common at 3% and 1.45%, respectively.⁶ Significant risk factors for cardiac complications included age > 65, congestive heart failure, positive cardiac and/or syncopal history, and increasing surgical invasiveness.^{6,16} These findings are consistent with those of Fujita et al, who demonstrated a 1.8% incidence of postoperative chest pain with electrocardiogram (EKG) abnormalities in 169 patients with an average age of 69.2 years undergoing multilevel thoracolumbar spine fusions.¹⁷ Similarly, in a retrospective review of posterior lumbar decompression and fusion in patients 65 and older, 3% of patients suffered a MI in the perioperative period.⁸

Myocardial infarction should be high on the differential diagnosis in the postoperative elderly spinal patient with chest pain; however, other etiologies should also be considered including pulmonary embolism (PE), pneumonia, or esophageal reflux. Evaluation for a cardiac source must be thoroughly pursued starting with a physical exam, assessment of vital signs and end-organ perfusion, as well as cardiopulmonary auscultation where crackles or a new murmur may be detected. An EKG should be performed immediately and compared to prior tracings, if available. ST segment depression with or without T-wave abnormalities may be present, indicating myocardial ischemia. Troponin levels should be obtained at symptom onset, 6 and 12 hours thereafter, as this cardiac biomarker may not be detectable until 4 hours after myocardial injury.¹⁸ Other studies such as chest X-ray, hemoglobin levels, or PE workup may be required as the clinical picture dictates. Cardiology consultation should be immediately obtained for management should there be evidence of myocardial ischemia or in the presence of high clinical suspicion.

The best treatment approach, however, is prevention. This begins in the office by identifying from history, symptoms, or medical conditions that may increase the patient's

risk of a perioperative cardiac event. Age >70, history of cardiac disease, diabetes mellitus, renal failure, angina, and poor functional status are a few of the clinical markers that warrant further investigation.¹⁹ Subsequent evaluation by the patient's primary care physician or cardiologist should be sought for medical optimization, risk stratification, and perioperative recommendations. One algorithm commonly used for preoperative cardiovascular evaluation for nonemergent surgery outlined by the American College of Cardiology/American Heart Association (ACC/AHA), stratifies risk based on the above clinical markers, functional capacity (e.g. ability to perform only ADLs versus sports activities), and risk level of surgery.¹⁹ This approach helps guide which patients may require further cardiac evaluation or intervention prior to proceeding to the operating room.

Once the decision has been made for surgical treatment, several steps can be taken to further mitigate the risk of a cardiac complication. Perioperative beta blockade may be used when clinically indicated which has shown to decrease the risk of cardiac death and MI by as much as 65–90%.^{20–22} Patients with impaired cardiac function may be placed further at risk due to the hemodynamic effects of prone positioning. Immediately preoperatively, adequate fluid replacement prior to induction of anesthesia minimizes these perturbations.²³ Furthermore, using transesophageal echocardiography, Dharmavaram et al. demonstrated that the use of a Jackson spine table or longitudinal bolsters, which allows the abdomen to hang free with the legs at heart level, permits adequate venous return and has the least effect on cardiac index.²⁴ Therefore, from the office to the operating room, utilizing these strategies and employing a multidisciplinary approach will decrease the patient's risk of perioperative cardiac complications.

■ VENOUS THROMBOEMBOLISM

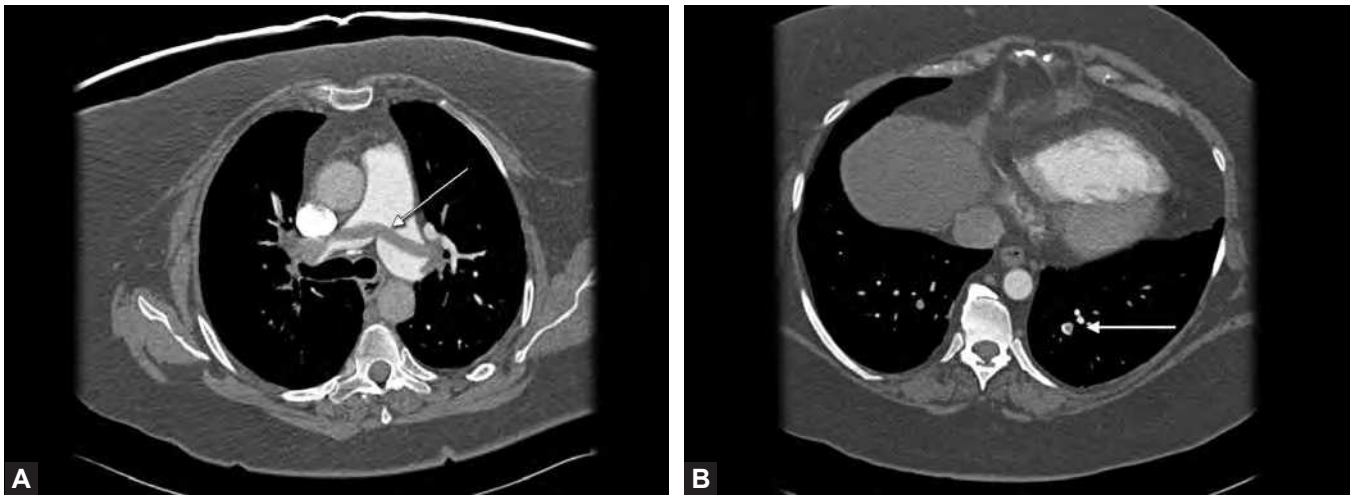
Surgeons face the issue of venous thromboembolism (VTE), which includes deep vein thrombosis (DVT) and PE, with every operation performed. A decision must be made on the form of prophylaxis and consideration to the type of treatment should a VTE occur. While pharmacologic prophylaxis may be complicated by wound hemorrhage and bleeding complications, such problems near the spine can have devastating sequelae.²⁵ As such, it is critical to consider the risks and benefits prior to initiation of pharmacologic VTE prophylaxis.

When deciding who should receive chemoprophylaxis, one must consider the underlying mechanism of clot formation, patient risk factors, and the type of surgery

performed. Rudolph Virchow described a triad of features that precipitate VTE: endothelial injury, venous stasis, and hypercoagulability.²⁶ Surgical dissection inevitably causes endothelial injury, especially with great vessel retraction during anterior procedures, which stimulates the coagulation cascade. Venous stasis occurs both intraoperatively during positioning and postoperatively due to bed rest and relative immobility. The final component of the triad, hypercoagulable states, encompasses both inherited and acquired disorders that predispose a patient to clot formation. The most common genetic susceptibilities for venous thrombosis are factor V Leiden and prothrombin mutations, with a 4% and 2% prevalence, respectively. Others include deficiencies in protein C, protein S, or antithrombin III. Malignancy, hormone replacement, oral contraceptives, and nephrotic syndrome are a few of the acquired hypercoagulable states.²⁷

Elective operations generally pose the lowest threat of VTE in spine surgery. Using only pneumatic compression stockings and duplex ultrasound screening, Epstein demonstrated a 2.8% DVT rate following lumbar laminectomy and instrumented fusion and a 1% VTE rate after single-level anterior cervical fusion.^{28,29} As surgical invasiveness increases, however, so does the risk of thromboembolic events. In a retrospective review of 361 adult patients undergoing spinal deformity surgery, a 2.4% PE rate was observed despite pharmacologic prophylaxis. Furthermore, patients who had an anterior approach were at significantly higher risk than posterior surgery.³⁰ A meta-analysis of 14 studies with a total of 4,383 patients reiterates the exceedingly low number of thromboembolic events following elective spine surgery. In the absence of any form of prophylaxis, DVT and PE were seen at rates of 5.8 and 0%, respectively. Using only intermittent pneumatic compression (IPC), rates occurred at 1.8 and 0.4%, respectively. When mechanical and pharmacologic prophylaxis (in the form of aspirin, low-molecular weight heparin, or warfarin) were combined, rates were <0.0001 and 0%. However, the latter group experienced eight epidural hematomas requiring surgical evacuation.³¹

Spinal cord injury (SCI) patients lie on the opposite end of the spectrum with regard to VTE risk. DVT occurs in >80% of these patients if no prophylaxis is utilized as opposed to a range of 8.5% to 21.7% with the use of pharmacologic agents.^{32–35} Furthermore, paraplegics actually have significantly higher rates of VTE than quadriplegics, supposedly due to the flaccid paralysis and increased venous stasis as opposed to spasticity seen in higher-level injuries.^{36,37}



Figs. 124.1A and B: (A) A central pulmonary embolism (PE) or “saddle embolus” (arrow) is more likely to be symptomatic, have a coexisting deep vein thrombosis, and carries a substantial risk of PE-related death. (B) A subsegmental PE (arrow) is incidentally detected 63% of the time and has a significantly lower risk of PE-related death.

Source: Images courtesy of Albert Song, MD, Loyola University Medical Center Radiology Department, Maywood, IL.

The American College of Chest Physicians (ACCP) guidelines for VTE prophylaxis recommend IPC, unfractionated heparin, or low molecular weight heparin for most patients undergoing spinal surgery.³⁹ Similarly, a systematic review by Glotzbecker et al. concluded that, given the low incidence of VTE following routine spine surgery, compression stockings with IPC should be the primary form of prophylaxis.³⁸ For high-risk patients, especially those with malignancy, an anterior-posterior approach, SCI, or surgery for spinal trauma, the ACCP recommends a combination of mechanical and pharmacologic prophylaxis. The chest guidelines acknowledge that the risk of major bleeding such as mass effect on the neural elements with neurologic deficit is likely <0.5% but is a potentially devastating complication.³⁹ As such, when selecting a method of anticoagulation, it is prudent to evaluate the entire clinical situation such as patient risk factors, extent of surgery, approach, and adequacy of hemostasis prior to chemoprophylaxis with close monitoring for any evidence of epidural hematoma if administered.

Signs and symptoms of DVT include calf pain, lower extremity edema, warmth, erythema, or Homan's sign; however, the physical exam is notoriously unreliable.⁴⁰ Laboratory evaluation, such as D-dimer level (which behaves like an acute-phase reactant), is also unreliable postoperatively as these values will be elevated in postsurgical patients. Although contrast venography is considered the gold standard diagnostic study, the best initial test is compression ultrasonography. With a sensitivity and specificity of 97–100% and 98–99%, this noninvasive test will

accurately detect the vast majority of clinically relevant deep vein thromboses.^{41,42} Similarly, many patients with PE do not exhibit hemoptysis, pleuritic chest pain, or circulatory collapse. Frequently, dyspnea and unexplained tachycardia are all that may be necessary to initiate a workup.⁴³ Spiral computed tomography angiography (CTA) has become the imaging study of choice for diagnosing pulmonary emboli. When compared to ventilation-perfusion scanning, CTA is able to identify other potential pathology and directly visualize the size and location of the emboli, including smaller, previously undetectable clots.^{44,45} This increased diagnostic ability must be considered prior to initiation of treatment, however, as the clinical relevance of these smaller PEs is unknown.⁴⁶

There are no established guidelines for the treatment of VTE after spine surgery. Management options, such as therapeutic anticoagulation or IVC filter placement, should be considered on a case-by-case basis. Important factors to consider include symptomatology, DVT location, and PE size. For example, symptomatic proximal DVTs account for >90% of acute pulmonary emboli and have a significantly higher mortality rate than those occurring below the knee.^{47,48} As for pulmonary emboli, large, central PEs are usually symptomatic with increased mortality risk, whereas small, subsegmental clots are often detected incidentally (Figs. 124.1A and B).⁴⁹ Finally, the benefits of treatment must be weighed against the risk of increased bleeding with potential for wound hematoma and/or paralysis.²⁵

DELIRIUM

Although neurologic deficits as a direct result of surgery are among the most worrisome following spinal procedures, medical causes are responsible for the majority of neurologic disturbances.⁵⁰ Delirium, an acute state of confusion, disorientation, and inattention with a waxing/waning course, is the most common neurologic complication.^{6,51-53} Elderly patients with poorer general physical condition are predisposed to developing delirium in the perioperative period. Pain, decreased mobility, psychological and physical stresses during hospitalization are frequently sufficient to precipitate postoperative delirium in a patient with an already decreased physiologic reserve.^{52,54} For example, up to 61% of elderly patients treated for femoral neck fractures develop delirium.⁵⁵ Although not as prevalent in spine surgery, mental status changes affect a substantial number of older patients. In a retrospective review to determine the incidence occurring specifically in postoperative spine patients, 13 of 341 patients (3.8%) developed delirium. All of these cases were in patients over 70 years of age, thereby representing an incidence of 12.5% in the elderly spine population in this study, which is consistent with other reports.^{8,50,56} Significant risk factors include preoperative dependence upon a wheelchair, greater number of preoperative oral medications (6.8 vs. 4.8), lower hemoglobin levels on postoperative day one (10 vs. 10.8 g/dL), emergency oncologic surgery, and primary spine infections.^{50,56} Delirium not only complicates the patient's postoperative course but leads to prolonged hospitalization and increased cost.^{55,57} Therefore, it is essential to identify patients at risk and be capable of efficiently managing this medical complication frequently encountered in the adult spinal patient.

The *Diagnostic and Statistical Manual of Mental Disorders* provides criteria that aid the clinician in the establishment of the diagnosis as well as differentiation from the gradual decline in cognitive function characterized by dementia. The four features include (1) a disturbance of consciousness with reduced ability to focus, sustain, or shift attention; (2) a change in cognition (memory, language, or orientation) or development of a perceptual disturbance that is not better accounted for by a preexisting, established, or evolving dementia; (3) development of the disturbance over a short period of time and fluctuation of symptoms during the course of a day; and (4) evidence from the history, physical examination, or laboratory findings that the disturbance is caused by direct physiologic consequences of a general medical condition.⁵⁸

Table 124.1: Deliriums.

<i>Causes of delirium</i>	<i>Examples</i>
D Drugs	Anticholinergics, antihistamines, benzodiazepines, opiates
E Eyes/Ears	Vision impairment, sensory deficits
L Low oxygen states	Myocardial infarction, pulmonary embolism, CVA
I Infection	UTI, surgical wound infection, sepsis
R Retention	Constipation, urinary retention
I Ictal state	Postseizure
U Underhydration	Dehydration
M Metabolic	Electrolyte and glucose abnormalities
S Subdural, Sleep deprivation	Intracranial hemorrhage

(CVA: Cerebrovascular accident; UTI: Urinary tract infection).

Once this acute confusional state has been recognized, identification of the etiology is paramount in order to provide quick and efficient treatment. Common culprits include medications and infections; however, various hypoxic and metabolic states may be responsible. A frequently taught mnemonic, *DELIRIUMS* (Table 124.1), is helpful in developing a differential diagnosis that can subsequently be used for directing management.⁵⁹

After assessment of vital signs and physical exam, appropriate labs and tests based on clinical suspicion may elucidate the source. Several initial steps may help resolve the delirium. For example, supplemental oxygen may acutely address causes of hypoxia; however, the underlying cause (e.g. postoperative anemia, MI) must be addressed. Medications known to precipitate mental status changes in the elderly such as anticholinergics and antihistamines should be discontinued and opioid analgesics minimized, if it all possible.⁶⁰ Metabolic causes, frequently sodium and glucose abnormalities, should be corrected and infectious etiologies (e.g. UTI, surgical wound) appropriately investigated and treated. If no source can be identified and the patient demonstrates continued symptoms and extreme agitation despite reorientation and correction of possible etiologies, small doses of sedatives such as haloperidol can be judiciously administered. Such pharmacologic treatment must be given cautiously, however, as these drugs can potentially prolong delirium in some patients.^{54,61}

Alcohol withdrawal should also be considered in the elderly patient with altered mental status. Signs and symptoms, beginning within 1–2 days of abstinence, include

hypertension, tachycardia, insomnia, and tremulousness. Delirium tremens, the most severe and dangerous form of alcohol withdrawal occurring after 4–5 days of abstinence, is characterized by hallucinations, severe autonomic instability, and seizures.⁶² Benzodiazepines and intensive care unit monitoring are often necessary in the management of this condition. Preoperative screening may help detect patients at high risk for alcohol withdrawal and appropriate prophylaxis with thiamine, folate, and benzodiazepines can be instituted.^{63,64}

CONCLUSION

Operative technique is only one component of a good surgical outcome. Multiple factors come into play when deciding on surgical intervention and when counseling a patient on an upcoming operation. The surgeon must be aware of and discuss with the patient that an increasing number of comorbidities may minimize potential therapeutic effects while simultaneously increasing the risk of perioperative complications. Especially in the elderly population, pneumonia, MI, thrombotic events, and delirium may seriously impair a patient's recovery and substantially increase morbidity and mortality. Therefore, it is imperative to identify patients at risk for poor surgical outcome or adverse medical events, and through a multidisciplinary approach, work to optimize the patient's health and efficiently treat perioperative complications in order to maximize the potential for a successful operation.

KEY POINTS

- Lumbar decompression for spinal stenosis is the most common operation for elderly patients undergoing spine surgery. Those with more comorbidities, especially cardiovascular disease, lower extremity arthritis, depression, and poor self-rated health have significantly worse outcomes than their healthy counterparts. These patients must be thoroughly counseled on surgical expectations and attempts made at medical optimization prior to surgical intervention.
- Older age and elevated surgical “invasiveness,” a function of the extent of decompression and instrumentation over a given number of spinal levels, significantly increase the risk of medical complications of nearly every organ system.
- Due to the relatively low risk of VTE in elective spine surgery, compressive stockings with IPC devices will

usually suffice for postoperative VTE prophylaxis. The addition of chemoprophylaxis should be considered for high-risk patients such as complex deformity operations, anterior approaches, spinal trauma and SCI patients, and those with malignancy or other hypercoagulable states. Patients receiving pharmacologic prophylaxis must be monitored closely for any signs or symptoms of epidural hematoma, which requires urgent evacuation.

- Postoperative pulmonary and cardiac complications increase risk of death >10- and fourfold within 2 years of surgery, respectively. As pneumonia and myocardial ischemia/infarction are among the commonest medical complications following spine surgery in the elderly patient, every effort must be made to identify those at risk and take appropriate measures to prevent such events.
- Above all, physicians must first “do no harm.” Any operation places the patient at substantial risk, both surgical and medical. Age, comorbidities, and extent of surgery must be contemplated prior to any elective operation. If the risk-to-benefit ratio is favorable for surgery, medical optimization with the assistance of other specialties should be sought out as indicated.

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- The most common operation in elderly spine patients is lumbar decompression for spinal stenosis. This study demonstrates that the most powerful predictors for inferior surgical outcome are cardiovascular comorbidity and poor self-rated health status.
- Lee MJ, Konodi MA, Cizik AM, et al. Risk factors for medical complication after spine surgery: a multivariate analysis of 1,591 patients. *Spine J.* 2012;12:197-206.
- This retrospective analysis of 1,591 patients describes the incidences and risk factors for medical complications after

spine surgery based on organ system. Age greater than 65 and increasing surgical invasiveness were significant risk factors for complications in five of the six organ systems evaluated.

Carreon LY, Puno RM, Dimar JR, et al. Perioperative complications of posterior lumbar decompression and arthrodesis in older adults. *J Bone Joint Surg Am.* 2003;85:2089-92.

The authors report the complication rates in patients age 65 years and older undergoing the most common surgical procedure in the adult spine population. 21% of patients had at least one major complication and 70% had at least one minor complication. Risk factors for developing a complication were increasing age and number of fused spinal levels.

Glottzbecker MP, Bono CM, Wood DK, et al. Thromboembolic disease in spinal surgery: a systematic review. *Spine (Phila Pa 1976).* 2009;34:291-303.

This literature review demonstrates the low rate of VTE and recommends that compressive stockings with intermittent pneumatic compression devices are usually sufficient for prophylaxis following most routine spine surgeries. The authors suggest that patients with increased VTE risks such as malignancy, prior VTE, neurologic deficit, or anterior approach should be considered for additional chemoprophylaxis or IVC filter placement.

Baron EM, Albert TJ. Medical complications of surgical treatment of adult spinal deformity and how to avoid them. *Spine (Phila Pa 1976).* 2006;31:S106-18.

This review article highlights the presentation, treatment, and prevention of medical complications that occur specifically following spinal deformity surgery. As these patients have among the highest risks of medical complications, many of the concepts discussed in this article can be applied to the general spine population.

Management of Cerebral Spinal Fluid Leaks

James T Dunlap, James D Kang

Snapshot

- » Epidemiology
- » Clinical Diagnosis
- » Treatment
- » Outcomes

INTRODUCTION

Disruption of the thecal sac is a relatively common occurrence in spinal surgery and may result from traumatic or iatrogenic injury causing a cerebrospinal fluid (CSF) leak. Durotomies can occur anywhere along the spinal column during surgery with a reported 3.1–3.84% incidence.^{1–3} Traumatic injuries such as burst and lamina fractures can also result in lacerations of the dura and are commonly associated with neurologic deficit.^{4–7} Most spinal surgeons will encounter dural tears (Fig. 125.1) during the course of their careers and therefore it is important to understand how to prevent them and, if present, manage them effectively.

EPIDEMIOLOGY

Traumatic

Traumatic dural injuries typically result as a laceration from an associated fracture in the vertebral body or lamina. In thoracolumbar and lumbar burst fractures, several studies have shown intraoperative findings of traumatic dural tears ranging from 10% to 19% occurring both anteriorly and posteriorly.^{4–6,8} Anterior dural lacerations were found in 10% of patients treated with anterior decompression. These tears were typically vertically oriented and likely a result of an asymmetrically retropulsed bone fragment as seen on preoperative computed tomography (CT) and were associated with a neurologic deficit.⁸

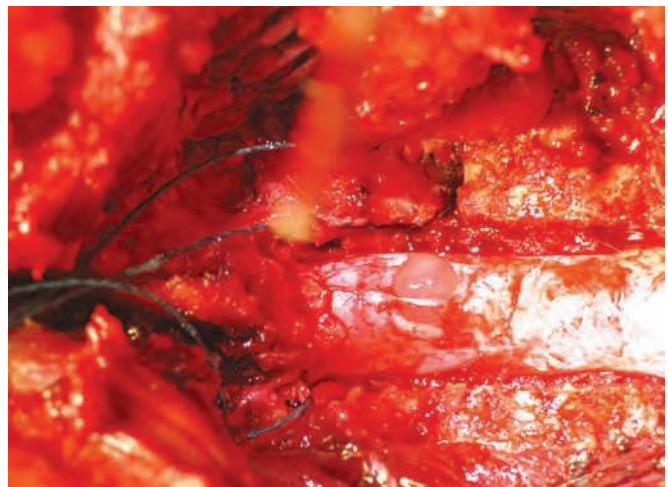


Fig. 125.1: Incidental dural tear with arachnoid membrane intact.

Posterior dural lacerations occurred as a result of lamina fractures in up to 19% of operatively treated patients, and of those patients, 36% were found to have neural elements entrapped between the fragments.^{5,6} Using current imaging techniques, it is difficult to identify lamina fractures with nerve root entrapment.⁵ The presence of a burst fracture, lamina fracture, and neurological deficit was highly predictive of a dural laceration.⁶

Iatrogenic

Iatrogenic dural injuries are one of the most common complications in spinal surgery and its rates vary widely



Fig. 125.2: Ossified posterior longitudinal ligament (OPLL). Patients with OPLL have the highest risk factor for incidental durotomies during anterior cervical procedures.

in the literature with reported rates of 1–17%.^{1,9–14} At one academic institution, a retrospective review of 3,000 elective spine surgery cases over a 15 years period revealed a 3.5% incidence of incidental durotomies with 1.3% in cervical, 6.6% in thoracic, and 5.9% in lumbar procedures. In addition, it was found that there was a 3.1% incidence in primary and 6.5% incidence in revision surgeries.³ Khan et al. also reviewed over 3,100 consecutive degenerative lumbar spine surgeries and found a 7.6% rate in primary versus 15.9% in revision cases.¹⁰

Several risk factors and mechanisms are associated with a dural tear and subsequent CSF leak. Revision surgery was the strongest risk factor (2.21 times more likely) for a dural tear while others include age (> 65), degenerative diagnosis, lumbar surgery, and surgical invasiveness (more levels and/or instrumentation).¹⁵ Scar tissue obfuscates the normal anatomy during dissection in revision cases, while in the elderly, the dura has been observed to be more fragile and thin. Surgeons tend to manipulate the dura more during lumbar surgery and especially so when operating on increasing number of levels, which therefore increases the risk of CSF leak. The risk of iatrogenic durotomy also increased for the surgical treatment across the spectrum of degenerative diagnosis—disc herniation (4%), stenosis (8%), and spondylolisthesis (11%).^{16–18}

In cervical spine procedures, the incidence of an iatrogenic durotomy was 1% with the highest risk in patients with an ossified posterior longitudinal ligament (OPLL) (Fig. 125.2) and second, in revision anterior cervical surgeries (anterior approach through prior incision).¹⁹ Other

reported risk factors for iatrogenic injury include limited surgical experience and improper technique.^{15,20,21}

The most common mechanisms of injury are direct trauma or lacerations during surgery. Factors involved include dissection of adherent tissue (ossification of the ligamentum flavum, fibrosis or scarring), lacerations from bony spikes during decompression maneuvers or from incorrect screw placement, or uncovering eroded dura.^{22,23} The primary surgical instrument involved in dural lacerations is the Kerrison rongeur as it is the most commonly used tool during lumbar decompression procedures.²¹

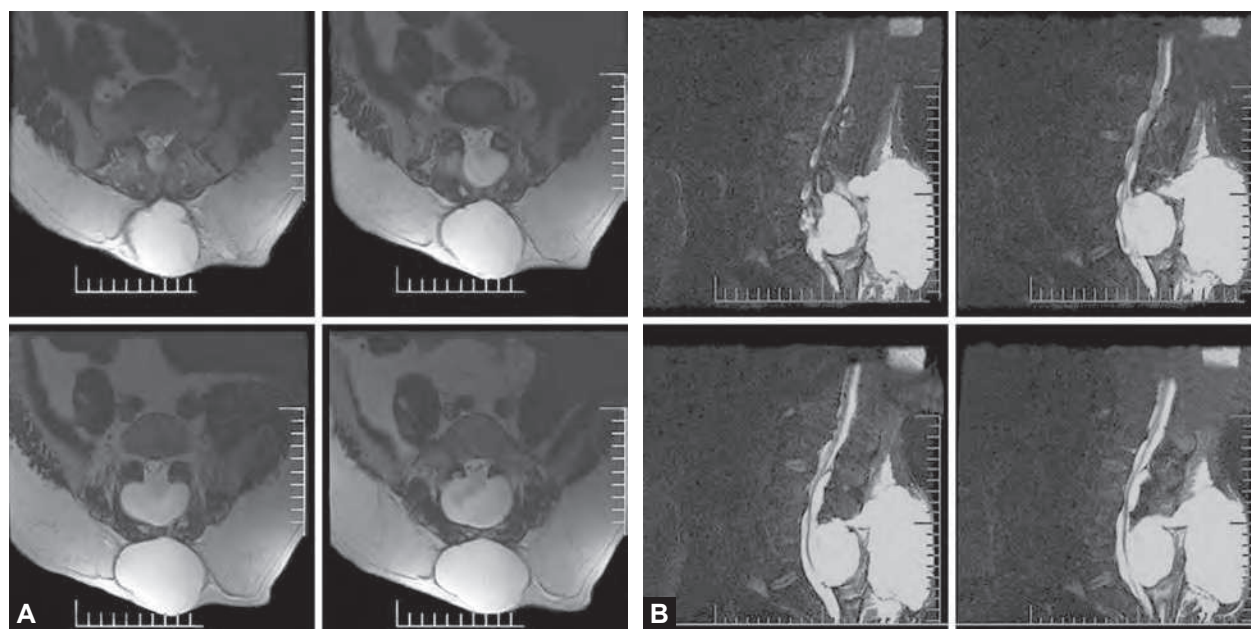
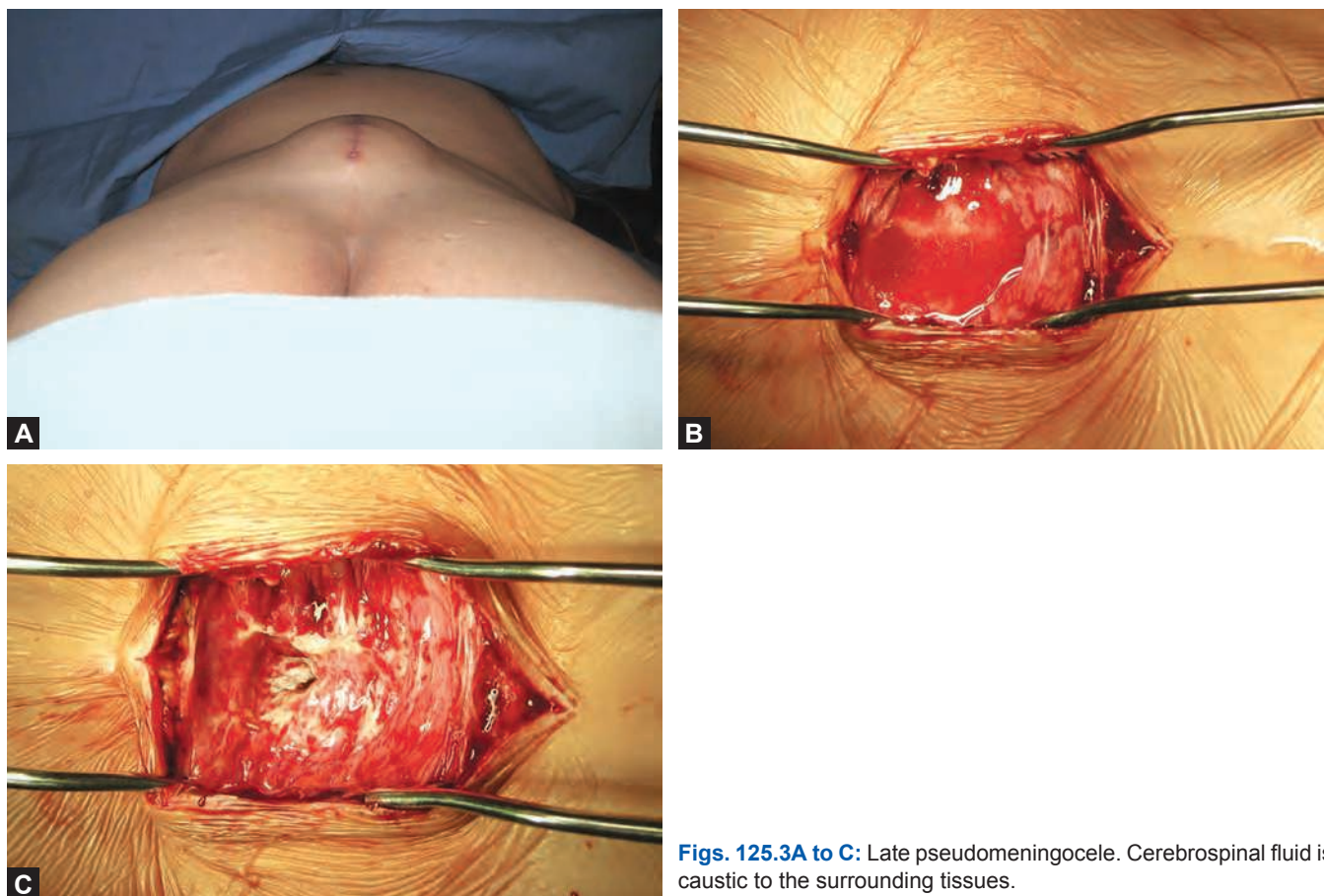
CLINICAL DIAGNOSIS

During the intraoperative setting, there may be direct visualization of the CSF leak through a dural tear. Indirect clues of a durotomy are the collapse of the thecal sac, pulsatile clear fluid in the field, or a sudden increase in epidural bleeding. Incomplete tears leaving the arachnoid membrane intact may result in no CSF leak intraoperatively but then burst open due to increased intra-abdominal pressure postoperatively.²²

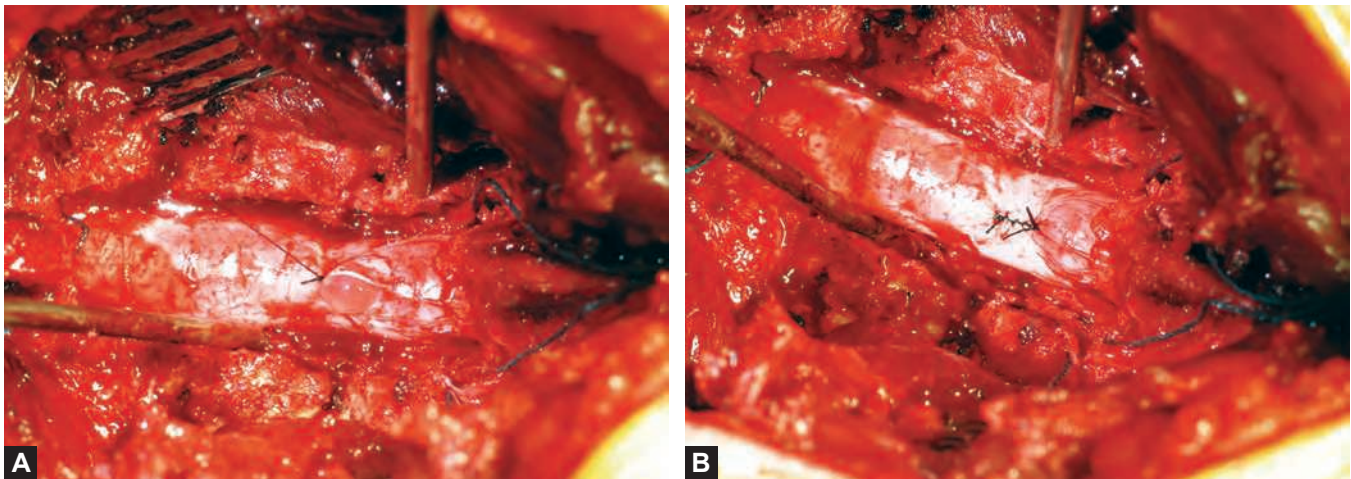
In the postoperative setting, diagnosis of a CSF leak may be more difficult but signs include patients with a postural headache, nausea, emesis, dizziness, and/or persistent serous or clear wound drainage. A CSF fistula may form within the first week of surgery. Evaluation for β -2 transferrin in the drainage, which is both sensitive and specific for CSF, can confirm the diagnosis.^{24–26} Dural tears presenting beyond 7 days postoperatively are uncommon (0.28%) and may be seen as a pseudomeningocele (Figs. 125.3A to C), an encapsulated extravasation of CSF fluid into the soft tissues.^{1,27} Pseudomeningoceles can develop at any time postoperatively and may first be noticed as an underlying fluctuant mass near the surgical site. Magnetic resonance imaging (Figs. 125.4A and B) or a CT myelogram can help confirm the presence of a CSF leak and the filling of a pseudomeningocele.²⁷

TREATMENT

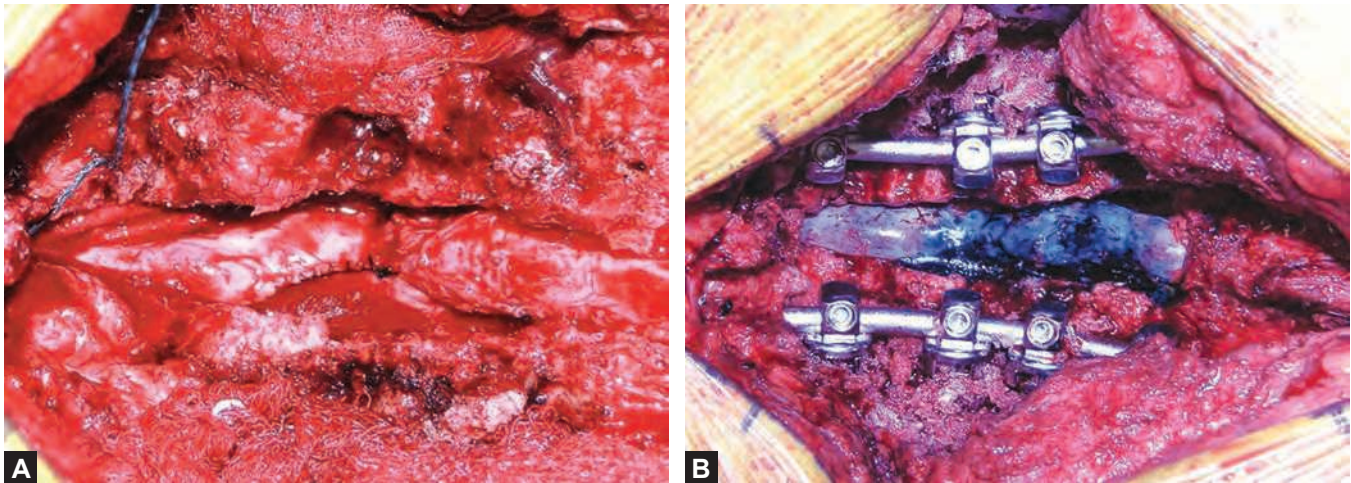
Ideally, prevention of dural tears is the most effective strategy by planning appropriately and using good surgical technique, but if an incidental durotomy occurs, primary watertight repair is the mainstay of treatment.^{9,11,13} To ensure optimal treatment, proper visualization is required to fully expose the dural tear. This may include appropriate hemostasis or further resection of bone and soft tissue. Once the edges are identified, suture repair is done in a



Figs. 125.4A and B: Magnetic resonance imaging T2 images demonstrating persistent cerebrospinal fluid leak with filling of a pseudomeningocele.



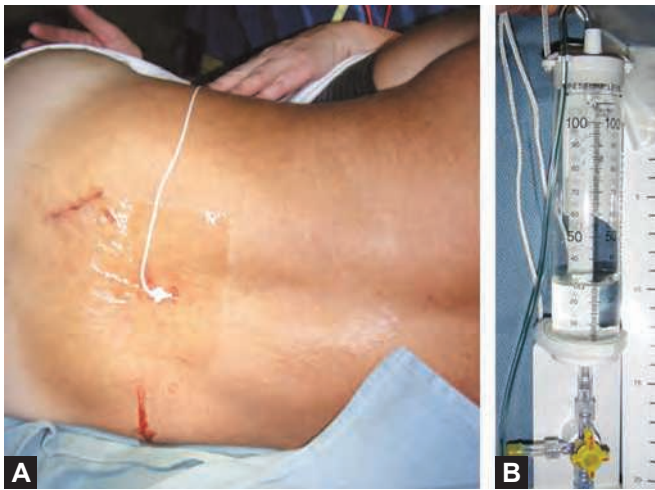
Figs. 125.5A and B: Watertight primary repair.



Figs. 125.6A and B: Primary repair before and after fibrin glue placement.

number of ways including running locked, simple running, or simple interrupted techniques. Size and type of sutures used vary from 4-0 to 5-0 silk, Prolene (Ethicon, Somerville, NJ), or Gore-tex (W.L. Gore, Flagstaff, AZ). Watertight repair (Figs. 125.5A and B) is essential and can be tested by increasing the intrathecal pressure using a Valsalva maneuver by the anesthesiologist. In the event that there is a persistent leak or the dural edges cannot be closed due to significant tension, a patch graft has been used. Due to the impermeability of fat and its lack of adherence to neural elements, these grafts have been used to plug dural defects with good effect.^{28,29} Other patch grafts used are muscle and fascia.^{1,13} Some authors advocate adjunct use of tissue sealants such as collagen matrix, fibrin glue, and hydrogel in addition to suture repair (Figs. 125.6A and B).³⁰⁻³³ Collagen

matrix has been used as an only graft in both primary and secondary means of closing the dura without any increased risk of complications and is replaced by natural collagen after 3 months.³¹⁻³³ The use of subfascial drains for bleeding with concomitant CSF leak is controversial but has been shown recently not to cause any increased adverse effects including formation of spinal cutaneous fistulas.^{10,13} In fact, one study showed successful healing of the dura despite a persistent CSF leak from the repair with prolonged drainage using a subfascial drain that helped prevent formation of a pseudomeningocele.³⁴ A tight layered closure especially the fascia helps to prevent egress of CSF that can slow wound healing and form fistulas or pseudomeningoceles possibly resulting in meningitis or neural injury.²² Primary repair of dural tears in the anterior cervical



Figs. 125.7A and B: Subarachnoid lumbar drain typically placed between L2 and L3. Typically titrated to equilibrate intra- and extrathecal pressure up to 360 mL/day depending upon symptoms.

spine may be difficult. Smaller tears have been covered with Gelfoam (Pfizer, New York, New York) or a collagen matrix, while larger tears are treated with subarachnoid drainage (Figs. 125.7A and B) either at the time of the index procedure or up to a week after for persistent leaks.^{19,31}

Postoperatively, the recommendation for bed rest varies from only in symptomatic patients to standard protocols of 1–3 days.^{13,35} Even with successful repair, patients may continue to exhibit symptoms due to decreased intracranial CSF for several days. Patient positioning depends upon location of the dural tear to reduce pressure along the repair.³⁶ Patients with cervical CSF leaks are positioned upright and those with thoracic or lumbar durotomies are placed flat. Indications of a successful repair include the lack or resolution of symptoms such as postural headache, nausea, dizziness as well as absence of clear drainage from the wound or the subfascial drain. Persistent CSF leak despite repair can be treated with compression such as abdominal binders as well as closed subarachnoid drainage titrated up to 360 mL/day depending on symptoms to equilibrate the CSF pressure between the intra- and extradural space with up to 92% resolution within 5 days.^{11,37} Other conservative treatment strategies for persistent CSF fistulas/leaks have included epidural blood patches and percutaneous fibrin sealant with varying degrees of success.^{38–40} Prompt surgical repair of the dura should be done in cases where conservative management has failed, neurologic symptoms develop, or the CSF leaks excessively.

Our Treatment Strategies for a Lumbar Dural Tear

1. Identify dural tear intraoperatively
2. Obtain appropriate exposure of the tear by resecting bone and soft-tissue as needed as well as maintaining hemostasis
3. Place a cottonoid pledget over the tear to prevent inadvertent injury to the nerve rootlets during exposure maneuvers and to maintain dural turgor
4. Ensure extruded nerve rootlets are gently placed back within the dura prior to repair
5. Perform a figure-of-8 repair of small defects and a running-locked suture repair of large defects using 5–0 Gore-Tex
6. Ask anesthesia to initiate a Valsalva maneuver to check for any leaks
7. If repair is watertight, no further action is needed but if there is still a small leak then use DuraGen as an adjunct
8. In the case of a tenuous repair, suture localized fat graft into position as a patch
9. Place a subfascial drain initially to suction then switch to gravity the morning after surgery, and finally discontinue on the third postoperative day
10. Perform a watertight closure of the fascial and skin layers
11. Give anti-emetics postoperatively to avoid increased intrathecal pressure associated with emesis
12. Keep supine in bed rest for 24 hours
13. Elevate head of bed at 30° for 8 hours. If asymptomatic, trial ambulation with assistance
14. Restart postoperative protocol if patient becomes symptomatic
15. If after 72 hours, the patient remains symptomatic and/or there is persistent clear wound drainage, explore the wound in the operating room with possible placement of a subfascial versus a subarachnoid drain
16. Re-start postoperative protocol as above.

Management of Dural Tears in the Cervical Spine Differ in the Following Ways

1. Repair directly, if amenable
2. If not repairable, especially common after anterior cervical discectomy procedures, place Gelfoam over the defect and consider lumbar subarachnoid shunt (observation only usually sufficient)

3. Place submuscular (anterior approach) or subfascial (posterior approach) drain to gravity. Discontinue anterior drain on postoperative day 1 or 2 and the posterior drain on day 2
4. Keep head of bed elevated at 30° overnight. If asymptomatic, trial ambulation with assistance
5. If after 72 hours, the patient remains symptomatic and/or there is persistent clear wound drainage, consider placement of a lumbar subarachnoid shunt.

OUTCOMES

Persistent CSF leaks from dural tears intraoperatively may result in loss of thecal sac hydrostatic pressure leading to poor visualization from epidural bleeding or expose nerve rootlets to injury. Surgical progress is slowed and exposes the patient to potential complications including neurologic symptoms (radicular, cauda equina), infection, subdural hematoma and hygroma and tonsillar herniation.⁴¹⁻⁴⁴ A feared complication, meningitis, occurs only 0.18% of the time.⁴⁵ Persistent CSF fistulas and formation of pseudomeningoceles increase the risk of complications such as meningitis, epidural abscess, wound healing delay or infection, arachnoiditis, and nerve root entrapment.⁴⁶⁻⁴⁹

Several studies have shown no long-term adverse effects from dural tears recognized and treated promptly and did not appear to increase the risk of neurologic injury, infection or arachnoiditis.^{1,13,14} An oft-cited study contrasts these results with a 10-year follow-up of patients with incidental durotomy after lumbar disc surgery that shows trends towards poorer outcomes including increased rates of back pain, headaches, and difficulty with daily activities though the reasons for this are not clearly understood.⁵⁰ From a medicolegal standpoint, incidental dural tears are the second-most common cause of malpractice lawsuits in spine surgery.⁵¹ It is therefore important to fully explain to patients preoperatively the incidence and potential risk of dural injuries, their signs and symptoms, and general treatment strategies. Though this may not obviate filing a malpractice suit, patients will at least be more informed participants in their surgical care.

SUMMARY

Dural tears may result from traumatic spinal pathology such as fractures or iatrogenic injuries during surgery. Incidental durotomies are one of the most common complications spine surgeons will face. Therefore, it is imperative to understand how to properly diagnose and treat dural

injuries. Prevention is the most important aspect with appropriate preoperative planning and meticulous surgical technique. Certain cases are at the higher risk of dural tears including revision procedures, cervical OPLL, elderly, and higher degrees of stenosis with associated spondylolisthesis. Effective treatment strategies begin with a watertight dural closure if amenable followed by adjunctive measures as needed and postoperative vigilance of signs and symptoms. Prompt recognition and treatment of dural injuries generally lead to good outcomes with no long-term negative consequences.

KEY POINTS

- The most common cause of CSF leaks is iatrogenic dural injury.
- Risk factors for intraoperative dural tears include revision procedures, increasing patient age, higher degree of spinal stenosis, and lack of appropriate surgical technique or experience.
- Most dural tears can be managed effectively with multiple intraoperative and postoperative techniques.
- Primary repair with watertight closure is the “gold standard.”
- Overall outcomes not affected when prompt diagnosis and treatment are initiated.

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- A review of 1,994 patients over an 11 years period for elective cervical spine surgery at an academic institution revealed an overall prevalence of CSF leaks as 1%. The highest risk factor (12.5%) was in patients with OPLL. Most patients were managed successfully with observation alone and showed no long-term sequelae.

Complications of Lumbosacral Spine Surgery

Sumihisa Orita, Kazuhisa Takahashi

Snapshot

- » Neurologic Injuries
- » Dural Injuries
- » Vascular Complications
- » Instrumentation Complications
- » Postoperative Spinal Infection

NEUROLOGIC INJURIES

Overview

Neurologic injuries can happen directly or indirectly: Direct causes are essentially mechanical: contusion, laceration, traction, compression, and thermal (cautery) damage to the nerves. Indirect causes include ischemia, compression, systemic hypotension, anemia, or poor oxygenation. Especially ischemia can lower the threshold for neural injury from mechanical etiologies and vice versa.

Central or peripheral neurologic recovery takes up to 12–18 months after the surgery. The spinal cord terminates at the L1–L2 level as the conus medullaris, which should be considered since it is less resistant to manipulation during surgeries around the level. Nerve root and peripheral nerve injury can result in varying degrees of pain, paresthesias, and weakness. Transient compression is more likely to affect sensory function, i.e. motor recovery tends to precede sensory recovery.

The lumbar sympathetic chain lies anterior to the psoas muscle and can be injured during retroperitoneal approaches to the lumbar spine manifesting as patient complaints of contralateral foot coolness. Preoperative investigation regarding anatomic anomalies is also important to avoid nerve injuries. Abnormal osseous anatomy (abnormal pedicle morphology, compressive osteophytes, ossified ligamentum flavum) can complicate the surgical

procedures. The superior hypogastric sympathetic plexus is at risk of injury during approaches to the L5–S1 disc space.^{1,2} Anterior injury can result in retrograde ejaculation, which misdirects the ejaculate into the bladder instead of through the urethra.³

To avoid and predict neural injuries, a variety of neuro-monitoring techniques are used to monitor neural conduction. The most common in current use for spinal surgery are somatosensory evoked potentials, transcranial electric motor evoked potentials, and electromyography.

Issues to be Concerned in Each Surgical Procedure

Decompression

Lateral margin of the nerve root (i.e. medial wall of the pedicle) should be identified. Nerve roots may be attenuated over a bulging disc and not recognized owing to their peculiar appearance placing them at injury risk. Forceful retraction of a nerve root lying within a stenotic neural foramen risks nerve root injury. After the decompression, nerve recovery may replace one symptom with another (e.g. pain in a given distribution may be replaced by paresthesia).

Discectomy

Large herniations with dorsal root displacement and anomalous nerve root anatomy (i.e. conjoined nerve roots

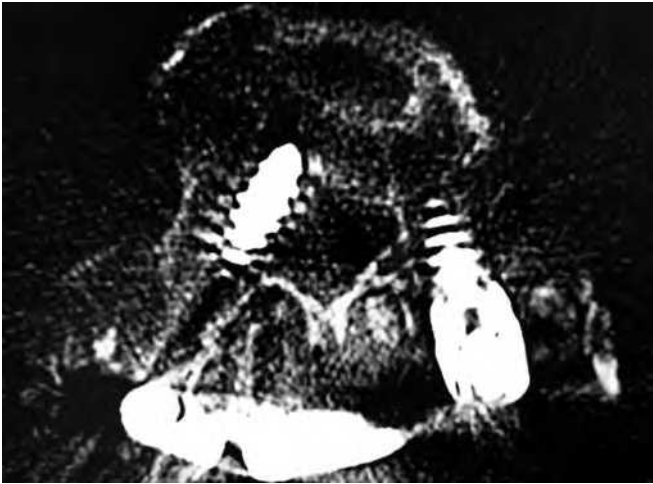


Fig. 126.1: The patient underwent lumbar decompression and instrumented fusion. The postoperative computed tomography showed a medial breach of the right L4 pedicle screw. The patient showed neither complaint nor neurodeficiency.

with inferior root displacement) can increase the risk of inadvertent injury. Upper lumbar disc herniations can pose a problem because obtaining adequate exposure is difficult due to the more narrow pars interarticularis and decreased tolerance for retraction of the thecal sac at these levels. Excessive retraction of nerve root or thecal sac risks neurologic injury and should be avoided.

Instrumentation

In the lumbosacral segment, the nerve roots lie along the inferomedial edge of the pedicle and are at risk of injury from medial and inferior pedicle breaches during pedicle screw placement. Intraoperatively consideration of anatomic landmarks, use of fluoroscopy, navigation system, and/or neuromonitoring techniques can be used to confirm appropriate placement. Pedicle screws should be directed such that they remain intraosseous to avoid critical adjacent neurovascular structures (Fig. 126.1).

Interbody Fusion Techniques

Neurologic injury can result from inappropriate graft placement or dislodgement, overly aggressive retraction in inserting the graft. Adequate exposure, gentle retraction to the degree necessary for safe implant placement, and careful discectomy technique help to minimize the risk of neurologic injury.

Durotomy Repair

Incidental durotomies can lead to neurologic complications if not handled properly. Dural injury is described in detail in the next section as well as a separate chapter in this textbook.

Bone Graft Harvest

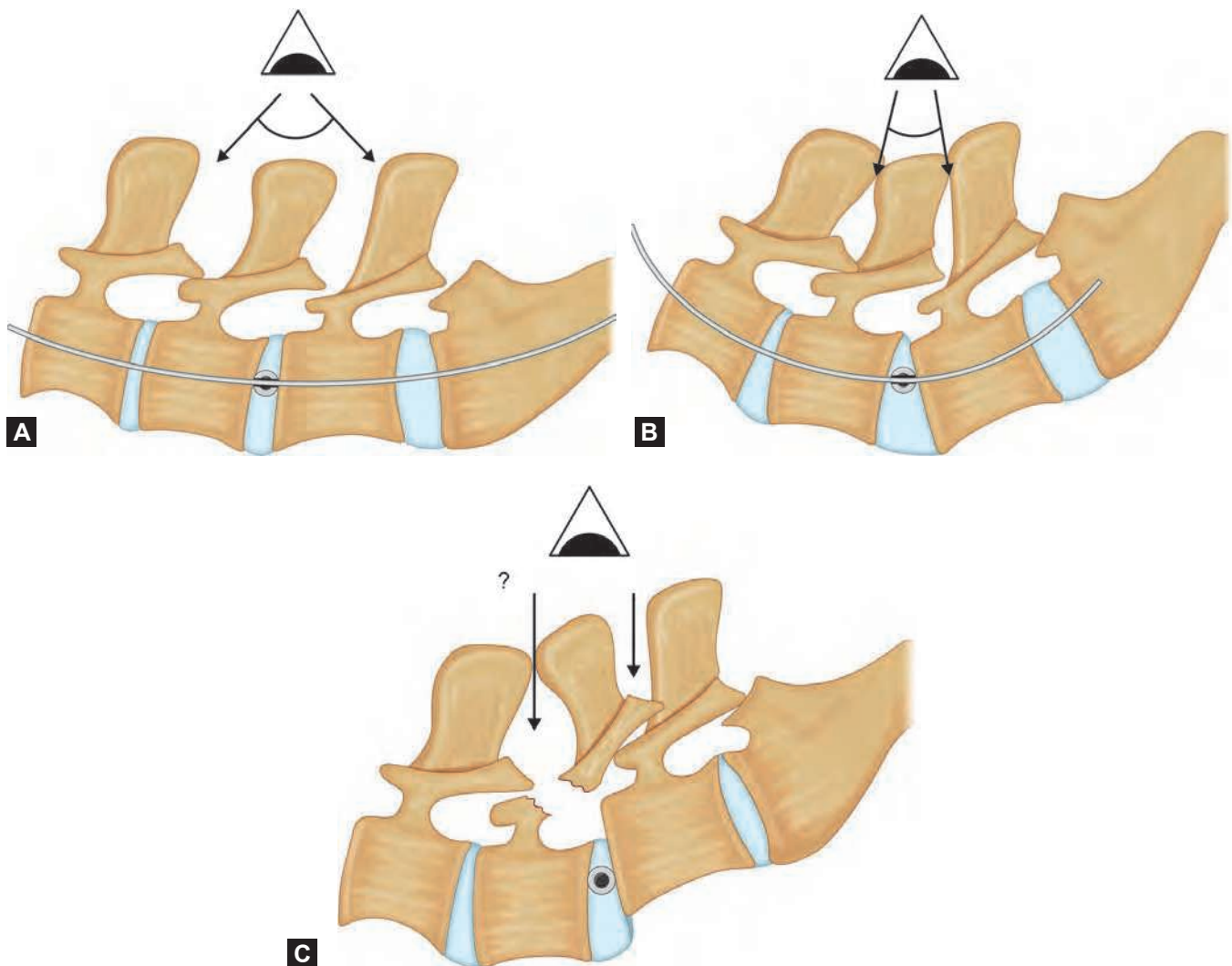
Harvesting of anterior or posterior iliac crest can lead to some cutaneous nerve injuries,^{4,5} resulting in painful neuromas and meralgia paresthetica: Harvesting bone graft from anterior approach may damage the lateral femoral cutaneous nerve, which provides sensation to the anterolateral thigh. It may be damaged during dissection within 3 cm posterior of the anterior superior iliac spine, while a posterior approach to the iliac crest may damage the superior cluneal nerves that are involved in sensation of the buttock if dissected >6 cm lateral to the posterior superior iliac spine.

Deformity Correction

Surgical management of spinal deformity is associated with an increased risk of neurologic injury.⁶ Neuromonitoring can help providing a safer surgical environment. Anterior exposures may require ligation of multiple adjacent segmental vessels, which carries a theoretical risk of clinically significant spinal cord ischemia. In patients undergoing deformity correction, the risk is minimal provided ligations are performed unilaterally and on the convexity.⁷ In patients without deformity, ligation of segmentals bilaterally at three levels or less can be safely performed.⁸ Excessive correction can result in mechanical or ischemic injury from kinking of the vasculature and cauda equina. Furthermore, direct vertebral derotation techniques through pedicle screws can risk fracture of the pedicle.

Wrong-Level Surgery

Severe spondylolisthesis or spondylolysis sometimes misleads the surgeons to wrong-level surgeries, which may cause the failed back surgery syndrome being a severe, long-lasting, disabling and relatively frequent complications (5–10%), as well as neurologic injury (Figs. 126.2A to C).⁹ Wrong-level surgery would be avoided by confirmation of surgical information including presurgical images and



Figs. 126.2A to C: (A) Normal alignment leads the surgeon to the correct level. (B) In case with increased lumbar lordosis, decreased interlaminar and interspinous space sometimes make it hard to identify the correct level. (C) In case with spondylolytic spondylolisthesis, surgeon can misidentify the adjacent level as the correct one.

enough knowledge regarding the pathology. The advent of intraoperative computed tomography (CT) scan imaging with equipment such as the O-Arm (Medtronic) and with the concomitant use of navigation, wrong level surgery can be minimized.

One of the other causes for wrong surgery is lumbosacral transitional vertebra,¹⁰ which is a congenital vertebral anomaly of the L5–S1 junction in the spine (Fig. 126.3). Definite manifestations are lumbarization of S1 (nonfusion between the first two sacral segments) or sacralization of the fifth lumbar vertebra (fusion between L5 and the first sacral segment). About 6.6% prevalence of six-lumbar-

vertebrae patients has been reported. This alteration may contribute to incorrect identification of a vertebral segment.¹¹

DURAL INJURIES

Overview

Incidental durotomy is a relatively common complication. Most of the dural injuries occur in the lumbosacral region with average 3.5% (1–17%) incidence.^{12,13} Signs and symptoms of dural leak include headache, nausea, vomiting, and persistent drainage of clear fluid from wound.

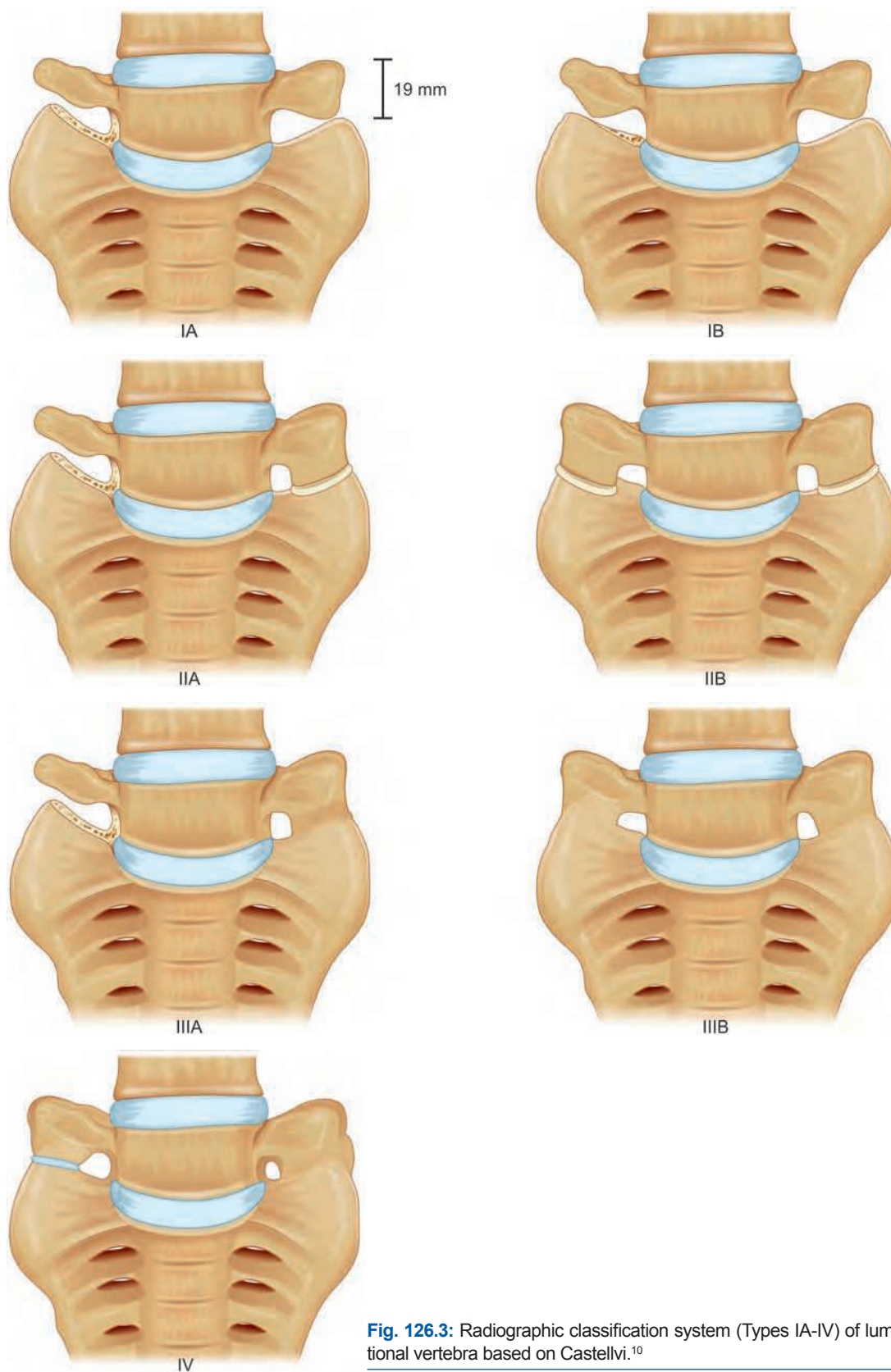


Fig. 126.3: Radiographic classification system (Types IA-IV) of lumbosacral transitional vertebra based on Castellvi.¹⁰

Dural disruption may result in subsequent cerebrospinal fluid (CSF) drainage and sometimes major or minor neurological disorders. An incidental durotomy is an unintended, often unavoidable tear of the dura mater during lumbosacral surgery. Dural disruption and subsequent CSF leak often occur from direct trauma or laceration, and dural entry is much more common in revision procedures (3.5% for primary discectomy, 8.5% for spinal stenosis surgery, and 13.2% for revision discectomy procedures.¹⁴) This is due to adhesions in the epidural space, dural scarring, fibrosis, and loss of surgical landmarks. Also iatrogenic surgical dural injuries were reported to amount to approximately twice as frequent (15.9% vs. 7.6%) in revision degenerative lumbar spine surgery.¹⁵ Conditions that increase the risk of a dural injury during primary spinal procedures include eroded or thin dura, adhesions and fibrosis, or dural redundancy in patients with severe spinal stenosis.¹⁶ The most common instrument leading to durotomy is the Kerrison punch followed by the curette and then the drill. Kerrison bites injury is the most common in the lateral gutters especially in areas of critical lateral recess stenosis, and medial bites during the surgery.¹³ Excessive traction on severely herniated discs and anatomically incorrect screw placement have also been described as causative factors for dural laceration¹⁷ as well as lack of surgical expertise and improper technique.¹⁸ However, McMahon et al. reported that they do not regard the years of physician training or resident experience as a major risk of incidental durotomy: residents and fellows as a whole accounted for 75% of all durotomies; however, rest of the incidence is due to attending surgeons. This means that the years of physician training or resident experience do not appear to be a major determinant of the risk of incidental durotomy.

Diagnosis

Incidental durotomy should be promptly diagnosed and repaired during the surgery, which will be exposed by a CSF leak intra/postoperatively. Late-presenting dural tears are much less common, having a frequency of 0.28%.¹² Persistently, clear or serosanguineous wound drainage following spinal surgery may suggest a dural tear and CSF fistula formation. If the diagnosis is in question, laboratory evaluation through electrophoresis for β -2-transferrin is useful, which is a sensitive and specific test for the presence of CSF.^{19–21} Postoperative fluctuant mass over the surgical site implies pseudomeningocele, which is due to the direct



Figs. 126.4A and B: Sagittal T2-weighted magnetic resonance imaging (A) and early phase postmyelogram sagittal reconstructed computed tomography (B) of postoperative lumbar spine demonstrating early filling of pseudomeningocele (arrow).¹³

CSF extravasation into soft tissues with eventual development of a fibrous capsule (Figs. 126.4A and B),²² which sometimes causes localized nerve root entrapment or adhesions leading to radicular symptoms. Therefore, postural headaches combined with increased sciatic pain may suggest the presence of a pseudomeningocele.^{23–25} Despite the frequency of dural tears in spinal surgery, meningitis is a rare complication reported to occur with a frequency of 0.18%.²⁶ In the situation of a persistent CSF fistula, the risk of meningitis, epidural abscess, arachnoiditis, delay of wound healing, or wound infection are all significantly increased.^{17,27,28}

Dural Repair

Careful preoperative planning and meticulous surgical technique can prevent CSF leak, particularly in patients at high risk of dural tears such as those with surgical revisions and Spondylolisthesis.¹⁷ The optimal treatment of incidental durotomies remains primary repair: Adequate exposure of the tear and surrounding normal dura is necessary for the proper repair of a dural opening. Primary repair is typically obtained by 5-0 or 6-0 silk, Prolene, or Gore-Tex sutures. In addition to sutures, adjuvant use of collagen matrix, fibrin glue, and Dermabond can be helpful.^{29–31} For tears that cannot be closed without undue tension on the thecal sac, the use of a patch graft is recommended using fat, fascial, and muscle grafts.^{12,31,32} After the repair, a tight fascial closure with nonabsorbable suture material is of extreme importance.¹⁷

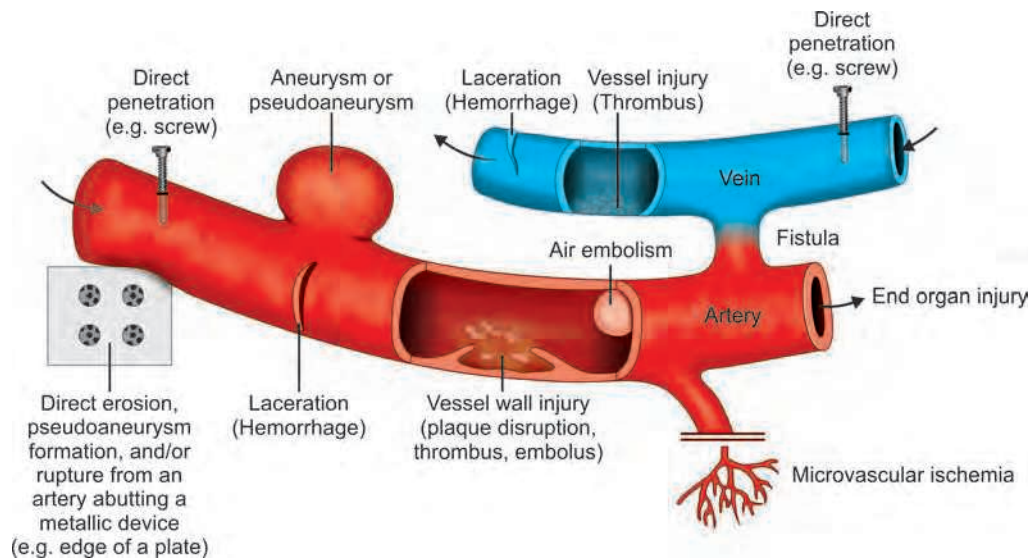


Fig. 126.5: The spectrum of vascular complications in spine surgery. A schematic diagram illustrating the spectrum of vascular injuries, complications, or sequelae associated with modern spine surgery, both anteriorly and posteriorly (or posterolaterally).³³

VASCULAR COMPLICATIONS

Overview

Vascular complication may arise directly from vascular injury or indirectly as a consequence of the injury (Fig. 126.5 and Table 126.1).³³ The most common vascular complication in spinal surgery is direct trauma to a vessel resulting in acute bleeding. Although venous lacerations are still most common, more arterial complications, especially occlusions and thrombosis, are being reported including deep vein thrombosis. Prevention of vascular complications is assisted by (1) knowledge of the vascular anatomy and common variants, (2) knowledge of the blood vessel and bone relationships, (3) gentle intraoperative techniques with appropriate illumination and magnification, and (4) preoperative planning.³³

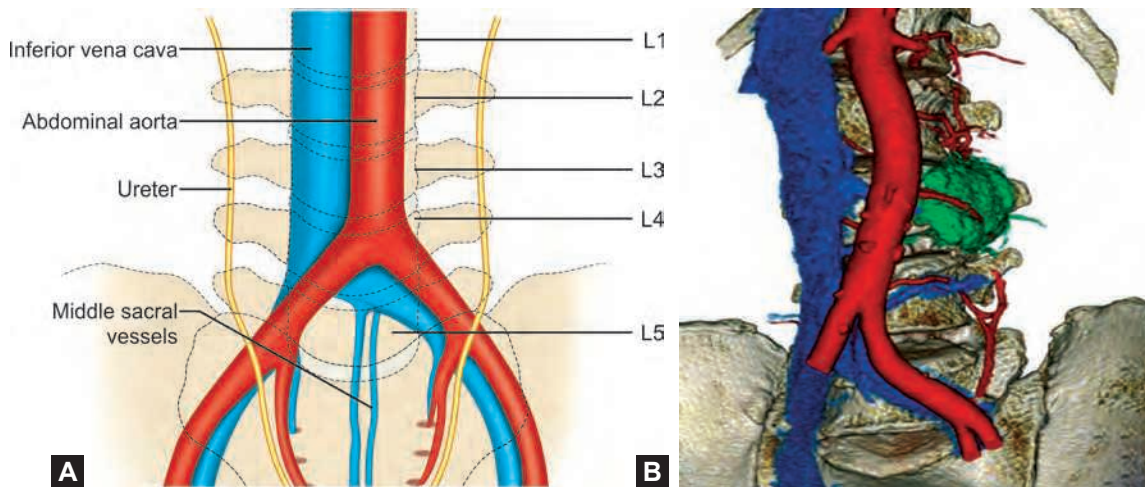
Lumbar Vascular Complications

Figure 126.6A shows the general anatomy in the anterior exposure of the lumbosacral spine.³⁴ Anterior approach gives us different orientation for the vascularities. Regardless of the type of anterior exposure, access to the vertebral bodies and intervertebral discs will require identification, mobilization, control, ligation, and/or protection of the arteries and veins that cover the anterior lumbar spine.³³ Preoperative imaging using reconstructed 3-dimensional images can be helpful (Fig. 126.6B). In the lateral or antero-

Table 126.1: Reported vascular complications in spinal surgery.

- Direct injury (anterior surgery)
 - Abdominal aorta/Vena cava
 - Common iliac arteries/veins (direct injury, fistula, aneurysms, thrombosis)
 - Internal iliac arteries/veins
 - External iliac arteries/veins
 - Lumbar segmental arteries/veins
 - Iliac artery thrombosis (retraction related)
 - Iliolumbar vein (direct injury, especially the left)
- Lumbar discectomy/Posterior approach interbody fusion
 - Vena cava and iliac vein from rongeur during posterior surgery
 - Superior rectal artery
 - Inferior mesenteric artery
- Iliac graft harvest
 - Superior gluteal arteries (posterior surgery)
 - Deep iliac circumflex artery (aneurysm from anterior surgery)
- SMA syndrome
 - Superior mesenteric artery

lateral exposure of the lumbar spine is most appropriate for pathology at or above L3–L4. The side of exposure is most often dictated by the pathology, however, the left side is usually chosen if all else is equal owing to the resiliency of the aorta compared with the vena cava. Considering the lateral or flank exposure of the retroperitoneum, the psoas major can be relaxed by flexing the hip and knee,

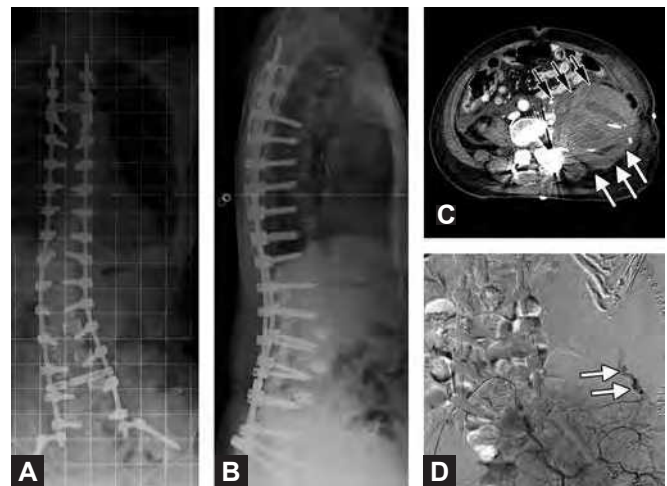


Figs. 126.6A and B: Transabdominal view of the abdominal aorta and inferior vena cava: (A) The vertebral column is posterior to the vessels. The aorta lies to the left of the vena cava. (B) Three-dimensional image reconstructed from enhanced computed tomography images of metastatic vertebral tumor patient. Segmental vessels from aorta and vena cava going toward the tumor (green) are depicted.

rendering vascular dissection safer and easier. Incisions are placed according to the vertebral level of interest, and the approach is carried to the retroperitoneal space. The psoas major is the key landmark to guiding the deep dissection. Each segmental vessel is independently isolated over the concave vertebral body with a right angle hemostat and clipped or ligated. Double ligation or clipping is preferred toward the great vessels, leaving at least 1 cm of lumbar segmental vessel to prevent making a hole in the aorta or vena cava.

Ligation of the segmental vessels should be over the middle of the vertebral body. By staying away from posterior ligation of the segmental vessels, the risk of interference with foraminal or collateral blood flow is reduced. If the ligature, suture, or clip should tear or dislodge, the major vessel can develop a large perforation in its sidewall. In addition, it is technically easier to control the vessels in this anatomic location. Emphasized four key vascular components and considerations for anterior lumbar exposure are as follows: (1) the iliolumbar vein, (2) the left iliac vein, (3) the middle sacral vessels, and (4) the type of arterial retraction so as to optimize exposure but minimize the risk of altered blood flow or displaced plaque.³⁵ Exposure of LS-S1 is probably the easiest vascular window: Previous magnetic resonance angiography-based study found that 18% of their cases showed the ilio-cava bifurcation occurred at or below the L5-S1 intervertebral disc space.³⁶

Vascular injuries and complications during anterior lumbar exposures rarely result in serious sequelae unless



Figs. 126.7A to D: A 70-year-old woman who underwent correction surgery for deformity (A and B). After the surgery, she showed hypovolemic shock due to the massive hemorrhage in the retroperitoneal space (C: arrows). Emergent intravenous radiology proved that the hemorrhage was due to the active bleeding from a branch of lumbar artery (D: arrows), which was controlled by the embolism using intravenous treatment.

the injury results in total disruption of the vascular channels to the lower extremity or other important viscera.³⁷ Prompt recognition and repair remain the standard of care.

Insufficient hemostasis in anterior approach can lead to fatal bleeding and hematoma as the approach lacks the chances of compressed hemostasis as is in posterior approach (Figs. 126.7A to D).

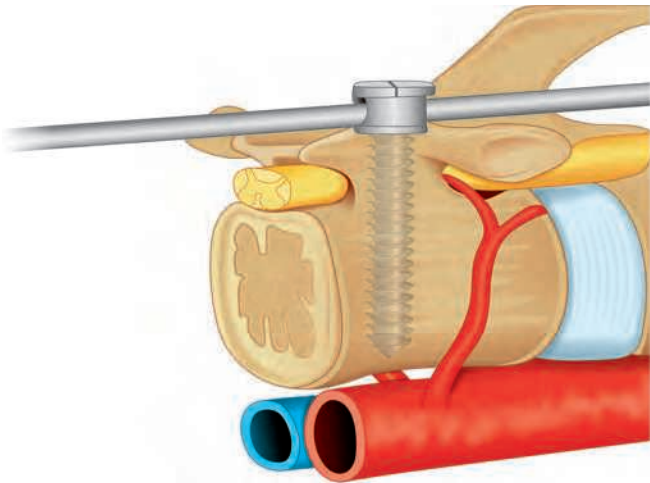


Fig. 126.8: The segmental vessels arising off the aorta form radicular branches that then pass through the neuroforamina to form the anterior and posterior spinal arteries.

The segmental vessels arising off the aorta form radicular branches that then pass through the neuroforamina to form the anterior and posterior spinal arteries, which should be taken care of in posterior lumbar surgeries (Fig. 126.8).

INSTRUMENTATION COMPLICATIONS

Spinal instrumentation complications can occur as a result of one or more than one of the following occurrences:³⁸

Biologic Failure

Infections can occur shortly after implant insertion or many years after the surgical procedure, which can be related to the presence of the hardware itself, the increased operative time associated with the instrumentation procedure or systemic infection. The next section addresses infection in detail.

The bone-implant interface integrity relies on the quality of the host bone and/or vertebral endplate. Osteoporosis can lead to early fixation failure or implant loosening before an attempted arthrodesis procedure heals. Deficient vertebral endplates or subchondral osteoporosis can lead to interbody device loosening or subsidence.^{39–41}

Pseudarthrosis may occur in even the most technically well-performed operation in an ideal, young, healthy, non-smoking patient. It is sometimes difficult to identify the pseudarthrosis until its associated micromotion results in pedicle screw or rod breakage.

Many other patient-related factors contribute to biologic failure and subsequent instrumentation complications: Steroid use, smoking, cancer, prior radiation therapy, multiple trauma, and poor nutrition. These factors can affect a patient's ability to heal a biologic procedure (fusion), diminish bone quality, and/or increase the risk of infection.³⁸ Nutritional status can be assessed and improved if surgery is elective. Smoking cessation before spinal reconstructive procedures can improve fusion rates: smoking delays a spinal fusion and may contribute to an increased incidence of instrumentation complications.⁴²

Biomechanical Failure

Biomechanical failure sometimes results in pedicle screw or rod loosening/breakage.⁴³ With any instrumented fusion, it is a race between failure of the instrumentation and healing of the fusion procedure. Without the presence of a bony fusion, instrumentation is ultimately likely to fail. In addition, poor bone quality may lead to limited purchase, failure at the bone-screw interface, or pull-out/toggle and weakening of the construct. Lumbosacral junction (LSJ) is a well-known lesion that would be damaged according to the increase in the length of the instrumented segment, leading to the incidence of adjacent segment disorder.⁴⁴ Especially destruction of L5–S1 facet joint can lead to devastated LSJ instability, which spine surgeons should take care of.

A retrospective clinical study has shown that sacral screw inserted in tricortical purchase, which penetrates into the apex of the sacral promontory, is the most rigid purchase compared with bicortical (penetrates anterior and posterior cortex) or monocortical (posterior cortex only) purchases.⁴⁵ It is also reported that long fusion can affect on the iliosacral joint, which implies the necessity of iliac screw fixation in long fusion surgery.⁴⁶

Lumbar interbody devices placed via a posterior interbody route (PLIF) can sometimes lead to the cauda equina and nerve roots at risk during insertion because of the retraction required to insert the cage^{47,48} These cages should be large enough to engage the disc endplates but not too large to force overretraction of the neurologic elements. Transforaminal cage insertion (transforaminal lumbar interbody fusion, TLIF) places the exiting and traversing nerve roots on the side of insertion at risk than the PLIF approach. Both PLIF and TLIF procedures destabilize the posterior tension band supporting structures and require supplement posterior stabilization.

Subsidence of the cage can result in subsequent pseudarthrosis, as well as loss of foraminal height resulting in radicular symptoms. In such situation, cage loosening or back out can happen. Previous study has reported a relationship between vertebral endplate cyst formation in the early postoperative period and nonunion after lumbar interbody fusion, suggesting that the endplate cyst formation is a useful early predictor of subsequent nonunion.⁴⁹

Error in Procedures/Application

In anterolateral approach, orientation and proper patient positioning are the first steps in avoiding aberrant screw placement with potential neurologic or great vessel injury. The anatomy can be deceiving in the operative room in patients with rotational deformities, local trauma, infection, or tumor. Screws should be directed anteriorly to minimize risks to the neural structures under the maintained direct lateral posture. In other words, inadvertent problems can occur if the spine/pelvis assumes a more oblique orientation during the surgery.

In posterior approach, pedicle screw-based systems are the workhorse instrumentation systems, with its complication rate of 2.4%. The most common complication is pain (23%) related to pseudarthrosis or the implant itself. Nerve root irritation was uncommon (0.2%) despite 1% of screws penetrating either medial or inferior to the pedicle wall.⁵⁰ The lower incidence of medial wall fractures and lower risk of neurologic injuries should be due to the anatomical features of relative thickness of the medial pedicle wall, and pedicle-nerve distance (1–2 mm). In another studies, the rate of implant removal due to pain is relatively low and nerve root irritation is also uncommon (range: 0.2% to 5% in various series).

Complications from other posterior implants, such as hooks and sublaminar wires, have been reported. Sublaminar wires run the risk of neurologic injury and cutting out of bone by sawing through the lamina, which sometimes represent a source of neurologic injury. Hooks should not be placed in regions of canal narrowing secondary to degenerative, traumatic, or deformity-based stenosis.⁵¹ In both approaches, osteoporosis can lead to loss of fixation and screw cutout into the disc space, plowing through the vertebra, or lifting off/backing out of the vertebral body. Osteoporosis or damage to the endplate can lead to excessive subsidence and loss of fixation.⁵² There have been some reports regarding perioperative osteoporosis treatment. Ohtori et al. have reported that daily subcutaneous

injection of teriparatide for bone union using local bone grafting after instrumented lumbar posterolateral fusion in osteoporotic women was more effective than oral administration of bisphosphonate.⁵³

POSTOPERATIVE SPINAL INFECTION

Incidence

Spinal infection rates range from approximately 1% for microdiscectomies to 5–6% for instrumented decompression and fusions.^{54–60} During the surgery cases requiring more extensive soft tissue dissection, longer operative time, greater blood loss, more significant soft tissue devitalization, or the creation of dead space has an increased infection rate.

Other theories postulate that local soft tissue inflammation and postoperative seromas may serve as a potential cause for the increased infection risk seen with instrumented fusions. Complete neurologic injury significantly increases the risk of postoperative infection with the rate ranging from 9% to 15% in the spinal trauma patients.^{61,62}

Classification

Two major classifications of postoperative spinal infections are shown below:

Severity: (1) Superficial or deep infection with a single organism, (2) deep infection with multiple organisms, and (3) deep infection and myonecrosis with multiple or resistant organisms.

Host response: (1) normal systemic defenses, metabolic capabilities, and vascularity; (2) local or multiple systemic diseases including cigarette smoking; and (3) immunocompromised or severely malnourished.

Risk Factors

We have to consider some risk factors for postoperative infection before surgery, which are divided into modifiable and nonmodifiable risk factors (Table 126.2).⁶³

For the patients with modifiable factors, surgeon should work on the patients to address the factors. Smokers have a significantly increased chance of developing postoperative infections.⁶⁴ Thus, smoking cessation counseling should be a routine part of the preoperative meeting between surgeons and patients. Obese patients are also considered at high risk of developing postoperative infections.^{65,66} Overweight patients often require more extensive

dissection through poorly vascularized adipose tissue. The resulting tissue devitalization and fat necrosis result in an environment favoring bacterial growth and proliferation. In addition, the increased operative time and blood loss necessary with obese patients increase their risk of infection. Obesity in itself is a risk factor for malnutrition, diabetes, and other medical comorbidities, further contributing to a poor healing environment with diminished immunogenic potential.

Malnutrition is seen in approximately 25% of all elective lumbar fusion patients, which should be considered preoperatively as a potentially modifiable factor.

Diabetes mellitus gives high incidents of postoperative infection of 17%. Elevated blood glucose concentrations, particularly those above 200 mg/dL, can inhibit host immune response including cellular chemotaxis and phagocytosis. In addition to creating a relatively immunocompromised state, poorly controlled diabetics are predisposed to chronic medical conditions including hypertension, cardiovascular disease, and renal insufficiency. Careful preoperative attention to tight blood glucose control and evaluating other related factors may limit the risk of local infection and systemic morbidity in diabetics.

Nonmodifiable risk factors shown in Table 126.2 can be optimized by enough evaluation before surgery. Although age is not considered an independent risk factor, older patients are more likely to have comorbidities associated with an increased risk of postoperative infection.

Table 126.2: Risk factors for postoperative spinal infections.

Modifiable	Nonmodifiable
Smoking	Rheumatoid arthritis
Obesity	Acquired immunodeficiency syndrome (AIDS)
Surgery length	Adrenocortical insufficiency
Prolonged indwelling catheter use	Long-term corticosteroid use
Length of hospital stay	Malignancy
Malnutrition	Pre- or postoperative local radiation
Serum albumin < 3.5 g/dL	
Total lymphocyte < 1500/mm ³	
Recent weight loss > 10 pounds	
Transferrin < 150 mg/dL	
Abnormal skinfold measurements	
Diabetes mellitus	
Malnutrition	

Microbiology

The potential sources for postoperative infections are (1) direct inoculation during the operative procedure (the most common), (2) contamination during the early postoperative period, and (3) hematogenous seeding.^{54,67,68} Especially, fecal contaminants are more likely to be involved in surgeries of the low lumbar or sacral regions; bladder or fecal incontinence may predispose to Gram-negative flora, especially with posterior lumbosacral incisions. Gram-positive cocci are the most common pathogens responsible for acute postoperative infections. The most commonly reported organism is *Staphylococcus aureus*, which causes >50% of the infections.^{54,65,69} Other common Gram-positive species include *Staphylococcus epidermidis* and β -hemolytic streptococci. Common Gram-negative organisms cultured from infected surgical sites include *Escherichia coli*, *Pseudomonas aeruginosa*, *Klebsiella pneumonia*, *Enterobacter cloacae*, *Bacteroides*, and *Proteus* species.⁶³

Infections that present >1 year after surgery are generally caused by low-virulence organisms such as coagulase-negative *Staphylococcus*, *Propionibacterium acnes*, and diphtheroids,^{70,71} those comprise normal skin flora. These low-virulent organisms are usually rapidly cleared by the host immune response with appropriate treatment and generally do not result in a clinical sepsis.

Hematogenous systemic spread can also cause surgical site infections. These infections are often associated with systemic illness and sometimes have grave consequences such as multisystem organ failure. Repeated cannulization of the venous system can lead to a higher incidence of Gram-negative infections.⁶⁵

Diagnosis

Clinical Presentation

Pain is the most common complaint. Patients will generally have an interval pain-free period immediately following the surgery for approximately 1–2 months and subsequently develop increasing pain over several weeks. This irregular postoperative course from pain free to painful gives us the suspicion of postoperative infection. Superficial wound infections generally present within 2 weeks of surgery with local pain, erythema, drainage, and warmth. This would be treated with local wound care and oral antibiotics for approximately 2 weeks. However, if a wound continues to drain after extensive local care or if the patient develops increasing operative site pain with the development of

constitutional symptoms, it must implies an underlying deep infection. Examination of the surgical site may reveal increased erythema, edema, tenderness to palpation, and drainage.

Late infection presenting >2 months after the surgery can be difficult to diagnose because of the lack of obvious symptoms. Increasing pain at the surgical site or the presence of constitutional symptoms should prompt suspicion of an underlying infection in either the early or late postoperative time periods.

Laboratory Testing

White blood count (WBC): An elevated WBC implies infection, but is not an absolute indicator. Neutrophils tend to increase in acute infection with fever, while lymphocytes in viral infections. In the early postoperative period, surgical stress can initiate intravascular leukocyte demargination that causes an increased WBC. In addition, lack of significant elevation in WBC does not necessarily rule out an infection, especially in patients with immunosuppression. Chronic slight elevation in WBC count may imply smoking.

Erythrocyte sedimentation rate (ESR): ESR elevates following the surgery and may not normalize until 3–6 weeks postoperatively.^{72,73} Peak ESR levels have been shown to correlate with the degree of invasiveness of the surgery, with more extensive surgeries causing higher ESR elevations than less invasive procedures.⁷⁴

C-reactive protein (CRP): CRP values rise sharply during the initial postoperative period and decreases baseline levels more rapidly. CRP levels generally peak on the third day postoperatively and return to baseline within 10–14 days. This rapid normalization makes CRP a more sensitive indicator of infection and a more useful diagnostic tool when determining the presence of infection, especially in the acute and subacute postoperative period.^{72–77} Abnormal elevation of these factors outside of the postoperative period can indicate the evidence of developing infection.

Blood cultures: Cultures can provide the information about the culprit organism; however, one obtained from the superficial wound is often contaminated with skin flora and can confuse the diagnostic workup. In case with suspicious contamination, early aspiration of a suspicious wound can be of use.⁷⁸ Also, cultures should be taken in a septic individual with temperature of over 38.5°C before the initiation of antibiotics. If the blood cultures are positive and provide identification of an organism, it can be presumed that the same organism is the cause of the spinal infection.

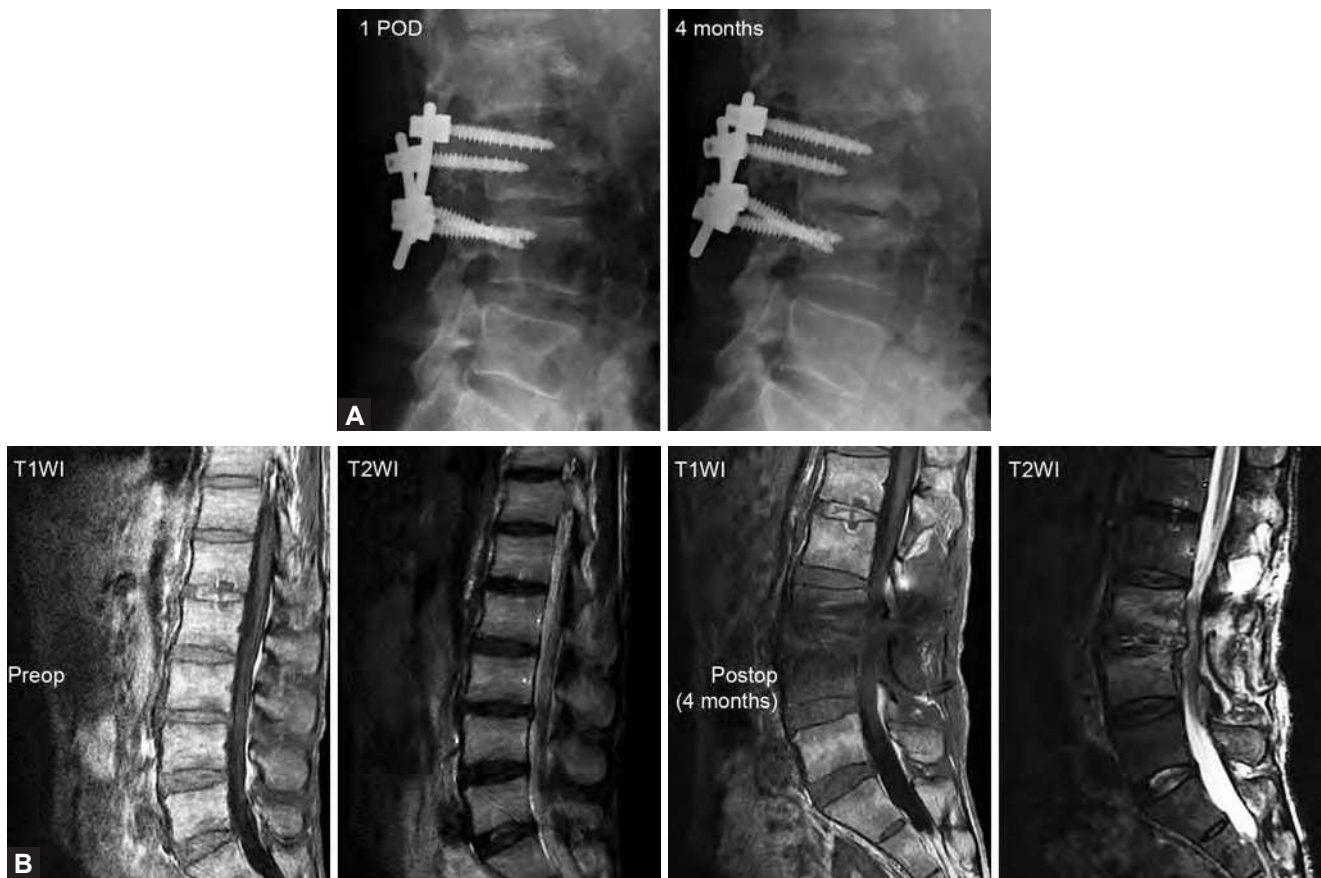
Imaging

Plain radiograph: Findings on plain radiographs are the first and basic clues for infection such as adjacent bony lysis adjacent to the instruments as well as their loosening, or disc space narrowing. However, these findings generally appear 4–6 weeks postoperatively, and often should require to be passed before the findings of infection up to 4 weeks.⁷⁵ More significant radiographic findings such as reactive bone formation, endplate destruction, osteolysis, and deformity indicate a more significant infectious process and usually require at least 2 months to develop.

CT: CT provides a more detailed view of spinal anatomy and evidence for the infection than plain radiograph does such as endplate changes, bony lysis, and/or soft tissue fluid collections. Computed tomography-guided biopsies can also be used to provide an aspirate for culture or tissue biopsy from infected soft tissue or bone as noted earlier.

Magnetic resonance imaging (MRI): MRI is the most important imaging modality with high accuracy (93% sensitivity and 96% specificity).^{79–81} Magnetic resonance imaging can identify postoperative osteomyelitis, discitis, and epidural abscesses. An epidural abscess will display a T1 isointense fluid collection with potential obliteration of the otherwise well-defined neural elements, and the T2-weighted images (WI) show significant increased intensity. Abscesses will display ring enhancement on T1 images following the addition of IV gadolinium. Osteomyelitis appears as areas of vertebral body and disc space hypointensity on T1WI and hyperintensity on T2WI. Discitis typically include hypointensity on T1WI and hyperintensity on T2WI in adjacent vertebral marrow (Figs. 126.9A and B). All cases of discitis displayed intervertebral disc signal enhancement with the addition of a contrast agent.⁸²

Nuclear medicine studies: Though its use is supplemental, it is helpful being free from the implant-associated artifacts unlike other modalities. Bone scans are often non-specific and may show generalized uptake around the surgical site in a postoperative spinal infection.⁷⁵ Technetium-labeled ciprofloxacin, when combined with single photon emission computed tomography, has been shown to have improved accuracy, particularly if performed >6 months after the surgery.⁸³ Recently, 18F-fluorodeoxyglucose-positron emission tomography has been reported to be of use for diagnosing pyogenic spondylitis in patients (Figs. 126.10A to D).⁸⁴



Figs. 126.9A and B: A 57-year-old man who underwent L3–L4 posterolateral fusion for lumbar spinal stenosis complained of lower back pain 4 months after the surgery and diagnosed as postsurgical discitis by the following radiographical examinations. (A) Plain radiograph shows the decreased interbody space with consolidation along the endplates and vacuum phenomenon. (B) Magnetic resonance imaging (MRI) shows low-intensity lesion in the disc and adjacent marrow (T1-weighted image) and high-intensity lesion in the corresponding area (T2-weighted image).



Figs. 126.10A to D: A 50-year-old man underwent posterolateral fusion surgery (A). Magnetic resonance imaging (MRI) indicated high-intensity lesion at the L4–L5 intervertebral disc level (B): T2-weighted image. Fluorodeoxyglucose-positron emission tomography showed abnormal accumulation in the L4–L5 level (C). The patient showed abnormal blood data (white blood cell 6200 cells/mm³ and C-reactive protein 2.70 mg/dL). Signs of infection on MRI were observed at the L4–L5 level 4 weeks later (D: T2-weighted image).⁸⁴

Prevention

The use of preparative prophylactic antibiotics is routine for most surgeons. Perioperative infection rate is 2.2–4.3% with preoperative antibiotics administration and 5.9–12.7% without.^{85,86}

In order for antibiotics to be effective prophylactic agents, they must have adequate spectrum and penetration ability into tissues adjacent to the surgical site in sufficient concentrations. Before the surgery, antibiotic administration should begin 30 minutes to 1 hour preoperatively followed by repeating after 4 hours of surgery.^{87,88}

Cephalosporin is an excellent candidate for prophylactic antibiotics for its good coverage against the common bacterial agents in spinal infection: First-generation cephalosporins are good antibiotics for prophylactic administration with strong gram-positive coverage (*S. aureus* and *S. epidermidis*) as well as against common gram-negative organisms (*E. coli* and *Proteus*). Cefazolin continues to be the most commonly administered prophylactic antibiotic for its appropriate antimicrobial coverage, relative inexpensiveness, and rapid elevation in systemic concentration.

Drug penetration should be considered and be maximally effective as the spine is composed of several different tissues from bone to soft tissue. Cefazolin displays a longer half-life in the serum and bone.^{86,89,90} Regarding the penetration of antibiotics into intervertebral discs, it varies according to the disc aging; Penetration of antibiotics into the adult intervertebral disc depends on passive diffusion from adjacent bony structures and cartilaginous endplates, as well as from the annulus fibrosus.⁹¹ Thus increased age and decreased disc vascularity inhibit the antibiotic penetration into the disc. Molecular charge of an antibiotic is an important determinant of its ability to diffuse into the disc. Positively charged antibiotics such as gentamicin and vancomycin have been shown to freely penetrate the annulus fibrosis and nucleus pulposus, whereas negatively charged antibiotics such as penicillin are found in the annulus fibrosis but not the nucleus pulposus. Recently, linezolid is a novel antibiotic that has been approved for treatment of methicillin-resistant *S. aureus* (MRSA) infections, and clinically attractive alternative to vancomycin due to its mild side effect profile and oral bioavailability, while it is reported to be inferior to vancomycin in experimental MRSA discitis rabbit models.⁹² Thus Linezolid can be inadequate for the treatment of spine infection limited to the intervertebral disc, but may be effective for

the treatment of infection extending into the muscle and bone marrow, such as in vertebral osteomyelitis, iliopsoas abscess, and postsurgical infection.⁹³ Antibiotics strategy should include antibiotic-resistant organisms, such as MRSA or vancomycin-resistant enterococci (VRE), which are associated with significantly increased morbidity, mortality, and cost. Some of the risk factors associated with MRSA include prolonged use of antibiotics, previous exposure or infection with MRSA, indwelling catheter use, advanced age, and intensive care unit stay.

Intravenous antibiotics are usually administered for approximately 6 weeks followed by approximately 6 weeks, or longer, oral antibiotics. The specific time for treatment depends on the virulence of the infectious organism and its sensitivity to the antibiotics. Regular follow-up of infectious laboratory markers including WBC, ESR, and CRP assists in determining the response to treatment.

Hematomas can occur and precede the infection at the surgical site by providing a significant milieu for bacteria proliferation. Postoperative closed suction drainage is useful to prevent hematomas. Limiting blood loss with meticulous attention to hemostasis, débridement of necrotic tissue, and periodic release of retractors helps to minimize possible sites of infection.⁹⁴ In patients with significant infections or soft tissue involvement, the use of reconstructive soft tissue techniques including flap coverage may be necessary.

Management

In managing postoperative spinal infection, prompt diagnosis with isolation of a specific organism and initiation of appropriate medical and surgical management are important. Primarily a minimum of two sets of blood cultures should be taken and WBC, ESR, and CRP measurements should be used to detect the infection and monitor the treatment. If those do not help to determine the organism, biopsy can be optional. After the identification of organism, appropriate antibiotic therapy should be initiated. Extremely superficial infections such as a stich abscess can be treated with 2 weeks of oral antibiotics. For any significant infection, however, a minimum of 6 weeks of intravenous antibiotics followed by 6 weeks of oral antibiotics should be used. In addition to the antibiotics, most significant superficial and deep infections will require surgical débridement. When involved in the infection, the deep fascial layers should be opened and all loose tissue and foreign material should be removed. Infectious specimens

should be investigated for bacterial studies including aerobic, anaerobic, fungal and acid-fast studies.

The ultimate goal of any intervention is eradication of the infection, adequate wound closure and maintenance of vertebral column stability. The approach to treatment often requires aggressive and sometimes repeated débridement to prevent recurrence of infection until the tissues appear clean and operative cultures are negative. Vacuum-assisted closure for deep infection after spinal instrumentation is useful in dealing with patients susceptible to wound infections, especially those with neuromuscular diseases such as Duchenne's muscular dystrophy and cerebral palsy.⁹⁵

In case of epidural abscess, early recognition and prompt intervention, particularly surgical débridement should be considered. With progression of the disease, the patient may show signs of increased back pain, systemic symptoms and eventually neurologic deficit. Diabetes patients sometimes show no fever and pain, which can be diagnosed using laboratory tests with ESR and CRP.

Spinal Instrumentation and Infections

The use of instrumentation in spinal procedures results in a higher risk of developing a postoperative infection with approximate incidence rate of 5–6%.^{54,70} Implants provide avascular surfaces on which bacteria can create a glycocalyx, which serves as a barrier to the host immune response and antibiotic treatment. Although recent titanium systems theoretically will decrease the affinity of bacteria to the surface of the device,⁹⁶ unintended wear debris may be greater with titanium implants in a developing pseudarthrosis with implant interface micromotion leading to a more robust inflammatory response.^{97,98}

The implants should be inspected during evaluating suspected infections, and if the implants show obvious signs of loosening, they should be removed and replaced if necessary. It is still to be discussed whether to remove the implant or not in postoperative infection. Some authors advocate complete removal of all instrumentation, independent of fixation and fusion status, because of the difficulty of eliminating the infection without removal.^{99–101} Leaving instrumentation at the time of débridement has been sometimes recommended to prevent possibly catastrophic spinal instability. If the infections persist, the instrumentation can be removed after the arthrodesis has been achieved; however, vertebral column malalignment, spinal cord compression, and paralysis are potential

complications associated with instability if fusion is not complete at the time of instrumentation removal.

KEY POINTS

- **Neurologic injuries:** Neurologic injuries can happen directly or indirectly, and if there is the potential for recovery, this may occur over 12–18 months. Be careful not to retract the nerves too hard especially at the L1–L2 level, i.e. the level of the conus medullaris. Deformity correction surgery involves potentially higher risk of neurologic injuries. Neuromonitoring is also helpful during the surgery.
- **Dural injuries:** Incidental durotomy occurs with average 3.5% incidence in primary discectomy and 13.2% in revision discectomy procedures. The most common instrument leading to durotomy is the Kerrison punch followed by the curette and then the drill. Every surgeon regardless of experience may encounter a durotomy. Careful preoperative planning and meticulous surgical technique can prevent durotomy in some but not all cases, and early diagnosis and repair is important during the surgery.
- **Vascular complications:** Direct or indirect injury causes vascular complications. Anterior approach tends to lead to more vascular complications because of the existence of great vessels in the retroperitoneal space. Insufficient hemostasis in anterior approaches can lead to fatal bleeding and hematoma as the approach lacks the chances of compressed hemostasis as is in posterior approach. In posterior approaches, the segmental vessels arising off the aorta form radicular branches that then pass through the neuroforamina to form the anterior and posterior spinal arteries.
- **Instrumentation complications:** Spinal instrumentation complications can mainly occur from biological, biomechanical, and procedural failures. Loosening, breakage, or infections in implants lead to biologic failures. In arthrodesis procedures, without the presence of a bony fusion, instrumentation is ultimately likely to fail. Surgeons have to carefully plan their instrumentation surgery preoperatively.
- **Postoperative spinal infection:** Spinal infection rates range from approximately 1% for microdiscectomies to 5–6% for instrumented decompression and fusions, involving superficial to deep tissue infections. The most commonly reported organism is

S. aureus followed by gram-positive species include *S. epidermidis* and β -hemolytic streptococci. Infections that present >1 year after surgery are generally caused by low-virulence organisms or through hematogenous seeding. Patients will generally have an interval pain-free period immediately following the surgery for approximately 1–2 months with increasing pain. Laboratory test using WBC, ESR, and CRP and blood cultures are needed. Routine preoperative prophylactic antibiotics using Cephalosporins or Cefazolin are recommended to prevent postsurgical infection.

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Management of Intraoperative Neurologic Loss

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Snapshot

- » Identification of High-Risk Factors
- » Mechanisms of Neurologic Injury
- » Neurologic Intraoperative Monitoring
- » Management of Intraoperative Neurologic Loss

INTRODUCTION

The current spinal instrumentation available has allowed more aggressive surgeries for better deformity correction, reconstruction, stabilization, and decompression. This is particularly so for the rigid screw and rod systems that allow translation and derotation in deformity correction, and maintains this correction as fusion along the spine takes place. However, together with their intrinsic benefits, these procedures do come with risks and complications. Having knowledge and understanding of potential complications, the surgeon is able to adequately educate the patient as to the surgical risks and benefits of the procedure, and improve patient safety.¹ Risk awareness provides the surgeon with a better chance of avoiding complications and managing any that occur.² More common complications of spine surgery include infection, implant failure, and nonunion; neurologic complications are the most devastating. Strong corrective forces applied to the spinal deformities have serious risks for neurologic deficit including loss of motor function in the lower extremities.³ Though the risk seems low, the overall effect is tremendous to the patient; therefore, it is imperative to discuss the risk of neurologic injury to the patient and the family before surgery (Table 127.1).⁴

Minimizing neurologic injury begins with careful preoperative evaluation, identifying risk factors present in the patient and adequate preparation before surgery. The surgical plan must be well designed using sufficient

preoperative imaging modalities, and having the appropriate equipment available for surgery including proper working instruments, intraoperative neurologic monitoring, and image intensifier. Accurate documentation of the surgical steps undertaken can help to identify the cause of signal change, avoiding delay in doing appropriate remedial action.¹³ Sufficient postoperative care should also be anticipated; therefore, the need for having the patient admitted at the intensive care unit should be foreseen. Identifying the complications comes with a thorough understanding of its etiology, enabling the surgeon to institute immediate management to minimize its ramifications.

IDENTIFICATION OF HIGH-RISK FACTORS

Before surgery, identify high-risk patients and adequately prepare them for surgery. Suffice to say that a careful history and accurate physical examination should be performed and findings should be well documented. Abnormalities or asymmetry in the neurologic examination or excessive back pain are a cause of concern. Absence or asymmetry of abdominal reflexes suggests an intraspinal lesion such as syringomyelia. Proper imaging and diagnostics should be performed before surgery. Computed tomography (CT) scans help to identify and describe bony abnormalities, such as hemivertebrae. Male gender, patients younger than 11 years old, and abnormal

Table 127.1: Risks of neurologic complications for different spine procedures.

<i>Procedure</i>	<i>Risk</i>	<i>Author</i>	<i>Comments</i>
Spinal deformity surgery	0.01–0.05%, 17%	Bridwell et al.; ⁵ Wilber et al. ⁶	
Scoliosis surgery	0.3–1.4%	Winter; ⁷ Coe et al. ⁸	
Combined AP scoliosis surgery	1.87%	Diab et al. ⁹	Increase from 1% in anterior alone
Spine surgery in pediatric population	2.2%	Thuett et al. ¹⁰	0.17% for actual rate of permanent deficit
PLIF and TLIF	4.9%	Chrastil and Patel ¹	Range 0–7% 7.3% (from 2% to 14%) risk of dural tear 5.3% (from 0% to 11%) risk of post-operative radiculopathy/radiculitis
Anterior cervical spine surgery	0.2–0.9%	Daniels ¹¹	Iatrogenic spinal cord injury
Scheuermann's kyphosis	1.9%	Coe et al. ¹²	

(PLIF: Posterior lumbar interbody fusion; TLIF: Transforaminal lumbar interbody fusion; AP: Anterior-posterior).

superficial abdominal reflexes were significantly associated with neural axis abnormalities; therefore, routine use of magnetic resonance imaging (MRI) in this subset of patients is recommended.¹⁴ Other considerations for pre-operative MRI scanning include left thoracic curve pattern in idiopathic scoliosis, particularly in male patients or patients with severe curve.¹⁵ A 21.7% prevalence rate for neural axis abnormalities in infantile idiopathic scoliosis has been reported,¹⁶ and proposed total spine MRI evaluation at the time of presentation in those with curves measuring $\geq 20^\circ$. However, more recently, in the largest evaluation of intraspinal anomalies in infantile idiopathic scoliosis, a lower percentage (13%) of neural axis abnormalities in MRI was reported, with the recommendation of close observation as opposed to immediate screening MRI in patients with presumed infantile idiopathic scoliosis (IIS) and a curve $>20^\circ$. Table 127.2 lists down patients with higher risks of intraspinal abnormalities, suggesting evaluation using an MRI should be done.^{17–19}

Patients with comorbidities and concurrent medications should also be recognized. Medications, such as anti-inflammatory medications and aspirin, should be withheld to minimize intraoperative and postoperative bleeding. Patients with cardiopulmonary comorbidities have been reported to carry a higher risk for having electrophysiological events during spine surgery.²⁰ The decreased cardiopulmonary reserve compromises their ability to oxygenate the blood increasing the risk for ischemic injury to the cord.

Age is an important factor as well, having an increased risk for neurologic injury in adults with long-standing

Table 127.2: Patients with higher intraspinal abnormalities (MRI suggested).

Infantile or juvenile idiopathic scoliosis
Congenital anomalies
Atypical curves in adolescent idiopathic scoliosis (including apex left thoracic curve, double thoracic curves)
Apical thoracic kyphosis
Rapidly progressive curvature
Excessive headaches, atypical back pain
Abnormal neurologic examination

Sources:

- Pahys JM, Samdani AE, Betz RR. Intraspinal anomalies in infantile idiopathic scoliosis: prevalence and role of magnetic resonance imaging. *Spine (Phila Pa 1976)*. 2009;34(12):E434-8.
- Davids JR, Chamberlin E, Blackhurst DW. Indications for magnetic resonance imaging in presumed adolescent idiopathic scoliosis. *J Bone Joint Surg Am*. 2004;86:2187-95.
- Morcuende JA, Dolan LA, Vazquez JD, et al. A prognostic model for the presence of neurogenic lesions in atypical idiopathic scoliosis. *Spine*. 2004;29:51-8.

deformities. A review of 683 spinal fusion procedures for Scheuermann's kyphosis (mean patient age at 21 years, range: 5–75 years), with the majority (73%) of patients ≤ 19 years old, reported that complications were more common among adults (22%) with the no difference on the overall incidence of complications between the posterior spinal instrumentation (PSF) (14.8%) and same-day ASF/PSF (16.9%) procedures.¹²

Incidence of ossification of posterior longitudinal ligament (OPLL) is found to be 70% in the cervical spine,

15% in the upper thoracic spine, and 15% in the proximal lumbar spine.²¹ In the thoracic spine, it is usually seen in the upper- and midthoracic spines of women who are older than 40 years.²² Due to the inherent anatomic and physiologic factors of the thoracic OPLL, surgical success appears to be less compared to cervical OPLL. Anatomic considerations of the thoracic spine include (1) kyphosis, limiting backward movement of the cord during posterior decompression; (2) relative avascularity of the thoracic cord compared to the cervical, making it more sensitive to ischemia during manipulation, and (3) the presence of the rib cage, limiting the exposure.²³ Since the ossified ligament is strongly adherent to the dura, direct removal is difficult and can compromise the cord during decompression. When OPLL occurs in conjunction with ossified yellow ligament (OYL), severe thoracic myelopathy can occur. Performing laminectomy can cause alteration in spinal alignment and may cause neurologic compromise during surgery.²⁴ This is due to the presence of the OPLL anteriorly that can cause impingement when alignment changes. Li advocates stabilizing the spine in situ rather than correct the kyphosis when performing instrument fixation in thoracic OPLL.²³

Kyphoscoliosis poses an increased risk for cord ischemia due to long-standing vasoconstriction of the spinal arteries²⁵ as well as the decreased radicular-medullary arteries in the thoracic region.²⁶ Therefore, acute distraction may reduce the vessel caliber, subsequently decreasing spinal cord blood volume (oxygenated hemoglobin plus deoxygenated hemoglobin). This was demonstrated by Macnab²⁷ using near infrared spectroscopy, wherein changes were evident within 1 second of the intervention beginning and return to the baseline at the end of each intervention.

Revision surgery poses an increased risk for morbidity because of its complexity and technical demand compared to primary surgeries. Raynor et al.²⁸ report a statistically significant higher incidence of true positive events in revision surgery (6.09%) versus primary surgeries (2.27%). Furthermore, he reports that intraoperative monitoring reduced the potential incidence of neurologic deficit. He concludes that revision spinal surgery and lack of improvement in IOM data despite intervention have a significantly higher risk of postoperative neurologic deficit.

Other procedures associated with high risk include vertebral osteotomies and kyphosis correction.^{9,29,30} With the innate stiffness of the thoracic column, the deformities are less flexible, and neural structures more sensitive in deformity correction. In posterior shortening procedures,

Table 127.3: High-risk conditions.

	Author
Neurofibromatosis	
Skeletal dysplasia	
Myelopathy	
Cervical kyphosis	
Spinal cord atrophy	
Spinal instability and fractures through long fused spinal segments	Daniels ¹¹
Adults with long-standing deformities (Scheuermann's kyphosis)	Coe et al. ¹²
Congenital scoliosis	SRS ³
Pre-existing neurological impairment	SRS ³
Previous traction	SRS ³
Scoliosis with hyperkyphosis	Lyon et al. ³¹
Cobb's angle > 90°	
Combined approach surgery	
Hypotension/significant hemorrhage (decreased spinal cord perfusion)	
Revision surgery	Raynor et al. ²⁸
Sagittal deformities (kyphosis, spondylolisthesis)	Bridwell et al., ⁵ Vitale et al., ²⁰ Coe et al. ¹²
Cardiopulmonary morbidities	Vitale et al. ²⁰

neurologic risk continues to be a feature in these surgeries.³⁰ Neurologic deficit can take place during abrupt subluxation, laminar impingement, or cord buckling. vertebral column resection (VCR) acutely destabilizes all three spinal columns; therefore, it is obligatory to use a temporary rod for stabilization before osteotomy, preventing deficit initiated by sudden translation. Restoring the anterior height by using cages or bone grafts can address excessive buckling (Table 127.3).³⁰

Identification of patients with difficulty in performing neurological intraoperative monitoring is imperative to have proper preparations. Patients with neuromuscular scoliosis were significantly less likely than adolescent idiopathic scoliosis to have successful motor-evoked potentials (MEPs) and less likely to have a successful somatosensory-evoked potential (SSEP). Successful MEP is less likely to be successful in patients with kyphosis than in idiopathic scoliosis. Both MEP and SSEP were significantly less likely

to be successful in patients with cerebral palsy. A study by Vitale showed 83% success rate with SSEP and 72% success rate with MEP monitoring in patients with neuromuscular deformity, lower than those for patients with idiopathic scoliosis.²⁰

MECHANISMS OF NEUROLOGIC INJURY

Neurologic injury can either be due to direct trauma or indirectly through an ischemic insult to the spinal cord. Some studies have demonstrated that postoperative sensory deficits are more likely to be caused by direct trauma to the dorsal columns, whereas paraplegia is more likely to result from an ischemic insult to the anterior and central portions of the cord.³² Direct trauma can be caused by structural injuries during exposure, decompression, and instrument placement, by laceration, compression, traction or avulsion injuries to neural elements. Indirect trauma is a result of disruption of the blood supply to the neural structures, resulting to ischemia and disruption of axoplasmic flow, as seen in excessive blood loss leading to hypotension. Physiologic variables, such as systemic blood pressure, intravascular volume, and blood hemoglobin concentration, affect blood flow and oxygen delivery to the spinal cord. Combined with structural changes to spinal cord vasculature, indirect injury to the neural elements is introduced and neurologic deficits might be produced. Hypotension may induce spinal cord ischemia even without spinal cord manipulation.³¹ Other maneuvers cause indirect trauma including excessive thecal sac retraction in stenotic patients, distraction of the spinal cord in a rigid spinal deformity, and cord compression after corrective maneuvers, leading to decreased vascular perfusion damaging neural structures.^{33–35} Compression of the thecal sac to <45% of its cross-sectional area can bring changes in motor and sensory conduction.³⁶ Postoperative hematoma formation can compress the neural structures leading to neurologic deficits; thus, meticulous hemostasis should be observed. Traction or direct compression also induces indirect injury to the neural structures as in improper positioning and lack of padding to cushion the patient during surgery leading to peripheral nerve injury after spinal surgery. The ulnar, posterior interosseous nerve, the peroneal and lateral femoral cutaneous nerves are prone to injury through external pressure.

Neurologic deficits can present with a spectrum of symptoms, from radicular pain, paresthesia, numbness and weakness, to complete loss of function. It can be stratified

according to severity, whether it is minor or major, complete or incomplete, or transient or permanent impairment. Minor deficits include radicular pain, which is the most commonly reported by postoperative symptom of neurologic injury.¹ Major deficit would encompass several roots with both motor and sensory deficits.

NEUROLOGIC INTRAOPERATIVE MONITORING

With the emergence of intraoperative monitoring, surgical neurologic deficit can be prevented.³⁷ It is most beneficial during critical stages of spine surgery when the risk of neurologic injury increases.³⁸ A reliable neurologic monitoring technique should be able to detect spinal cord injury when it has been incurred, allowing the surgeon prompt recognition of the injury and appropriate corrective measures can be taken immediately, preventing irreversible neural structure damage and optimizing the chance for recovery. The ideal monitoring technique should be able to provide prompt warning but with minimal surgical interruptions; it should be reproducible and measurable. Stimulation can be applied to peripheral nerve sites to the motor cortex site on the scalp or directly to the spinal cord and recordings are taken accordingly. Evoked potential signals recorded at the dura are more stable than those from the scalp.³⁷

Spinal cord monitoring should be considered as an integral part of surgery for spinal deformity, allowing early detection of complications and possibly prevent neurologic morbidity in patients undergoing spine surgery,^{3,28,39,40} particularly for corrections of scoliosis >45° and in congenital spinal anomalies.⁴¹ It has been demonstrated that intraoperative spinal cord monitoring facilitates detection of impending spinal cord deficit and early responses that are likely to preserve spinal cord function.⁴⁰ The wake-up test can be a functional supplement in the detection of neurologic spinal cord deficits.³

False-negative cases refer to those in which the evoked potentials (EP) remain stable throughout the surgical procedure but the patient was found to have a postoperative neurologic deficit. False-positive results are those in which the EP changes that could not be related to any event that might imperil the cord function but the patient did not present with any postoperative neurologic deficit. A true negative outcome did not show any significant intraoperative change in EP and patient did not have any postoperative neurologic sequelae. A true positive result is defined as a change in the waveform that could be correlated with

Table 127.4: Interpretation of results.

	<i>True positive</i>	<i>True negative</i>	<i>False positive</i>	<i>False negative</i>
EP change	+	–	+	–
Neurologic deficit	+	–	–	+

a surgical event with or without a postoperative neurologic deficit. A false-positive warning rate of 2.2% was reported by Luk et al.³⁸ SRS survey as reported by Nuwer⁴² showed the overall false-negative rate to be 0.127% and the overall false-positive rate to be 1.51% (Table 127.4).

Abnormalities in recordings can be detected during curve correction, hypotension (MAP < 50 mm Hg), direct cord trauma, and malposition in pedicle screw.^{20,41} Other causes for loss or significant degradation of monitoring data, as identified by Thuet,¹⁰ include instrumentation, wound or nerve root retraction, halo/femoral traction, malposition or compression of peripheral limb, hemostatic matrix in spinal canal, and partially occluded endotracheal tube. Lotto⁴¹ also attributes signal changes to hypothermia and hyperthermia.

Somatosensory-Evoked Potential

Developed in the 1970s, SSEP monitoring serves as an early warning technique in detecting deficit during surgery.^{43,44} Somatosensory-evoked potential monitoring assesses the functional status of peripheral nerves and the dorsal sensory pathways (tactile discrimination, vibration, proprioception). The sensory-evoked potential (SEP) is the electrical response of the brain to an applied somatosensory stimulus; response is elicited by stimulating either a sensory or mixed peripheral nerve (median nerve, ulnar nerve, posterior tibial nerve, peroneal nerve) caudal to the operative site and can be recorded cranial to the operative site, like the scalp. The ulnar nerve is the preferred stimulation site for upper extremity SSEPs because the lower spinal nerve entry between C7 and T1 permits assessment of the entire cervical neural axis (Fig. 127.1).⁴⁴

Parameters continuously monitored throughout surgery include waveform amplitude (power of the signal) and latency (velocity of the signal) and compared with baseline, detecting injury.^{44,45} Amplitude and latency are recorded before skin incision and used as a reference baseline for subsequent monitoring. Change in amplitude is more sensitive to cord injury as it is unlikely to have injury without amplitude changes, while changes in latency

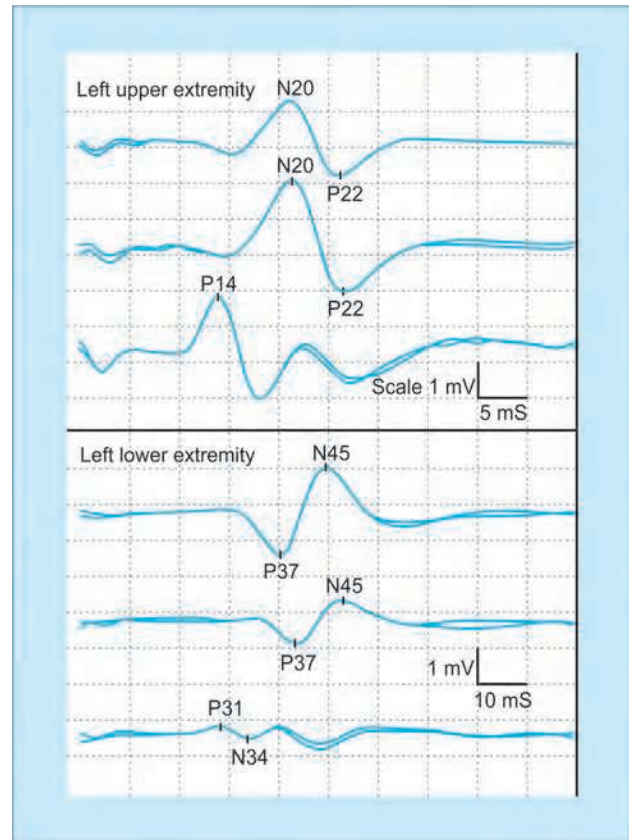


Fig. 127.1: Normal amplitude and latency. Amplitude is the power of the signal, while latency is the velocity of the signal.

are less relevant.⁴⁴ Data should be constantly updated to control for anesthetic and metabolic changes. Amplitude is sensitive to nitrous oxide, halogenated agents, hypothermia, hypotension, and electrical interference, while latency is affected by temperature. Chemically paralyzing the patient, such as in total intravenous anesthesia, diminishes myogenic interference enhancing the quality of response.⁴⁴ Baselines may be altered during different stages of surgery and should be noted before surgical procedures that may alter neurologic function such as deformity correction. Injury to the neurologic structures causes signal change such as decrease in amplitude and increase in latency. A 50% reduction in the amplitude or a 10% increase in latency is considered abnormal, requiring the surgeon's prompt attention.^{38,40,46} Alarm criteria vary from center to center but generally include an intraoperative unilateral or bilateral amplitude loss of at least 50–60%.⁴⁴ In our institution, another criteria which is >10 minutes of SSEP change is also used as an alarm criteria, as well as drop in amplitude differentiated into “quick change” that shows a decrease in amplitude to 30% within

30 minutes and “slow change” where amplitude drops to 60% for over 30 minutes (Fig. 127.2).¹³

It has been reported that marked changes in SSEP responses indicated a high chance of developing neurological deficit, and if there was no change, the chance of any neurological postoperative deficit was extremely low.^{28,47} Although it has safely reduced the risk of permanent neurological deficit, there are reports of false-negative cases where the patient awoke with a neural deficit not detected by SSEP.⁴⁰ There have been reports of paralysis, though rare, despite normal results of somatosensory monitoring.²⁰ Somatosensory-evoked potential monitoring is limited in that it can best detect injury limited to the ascending tracts but can give only indirect information about motor tracts. Therefore, damage to the motor tracts can occur without any resultant change in SSEPs. Somatosensory-evoked potentials have been reported to be 99% sensitive but only 27% specific in identifying neurologic deterioration.⁴⁸ There is a small but definite risk of false-negative findings when monitoring patients with pre-existing spinal cord compromise, such as myelopathy or acute spinal cord injury because of the sensitivity of the vascular supply to both the anterior and lateral aspects of the spinal cord, which is supplied by the anterior spinal artery. Hypotension-induced ischemic injury may not be detectable by SSEP monitoring at all or during the critical time needed to initiate intervention to prevent or minimize neural injury.⁴⁹ Recording SSEPs in patients with severe myelopathy, spinal cord tumor, obesity, or peripheral neuropathy either alone or in combination have also been shown to be difficult (Fig. 127.3).⁴⁴

Motor-Evoked Potentials

However, motor pathways are analyzed by MEP, thus has the advantage of detecting trauma to the descending motor tracts.²⁰ Response is elicited from motor pathways, including the corticospinal tract (CST), spinal cord interneurons, anterior horn cells, peripheral nerves, and skeletal muscles innervated by alpha motor neurons, after application of high-voltage transcranial electrical stimulus. A low-output impedance electrical stimulator generates a high-volume, short-duration stimulus or pulse train by a series of electrodes placed over different areas of the scalp to excite a specific motor cortical region, resulting to stimulation of CST axons coursing from the cortex through the internal capsule to the caudal medulla where the fibers cross over in the lower lateral brainstem and descend

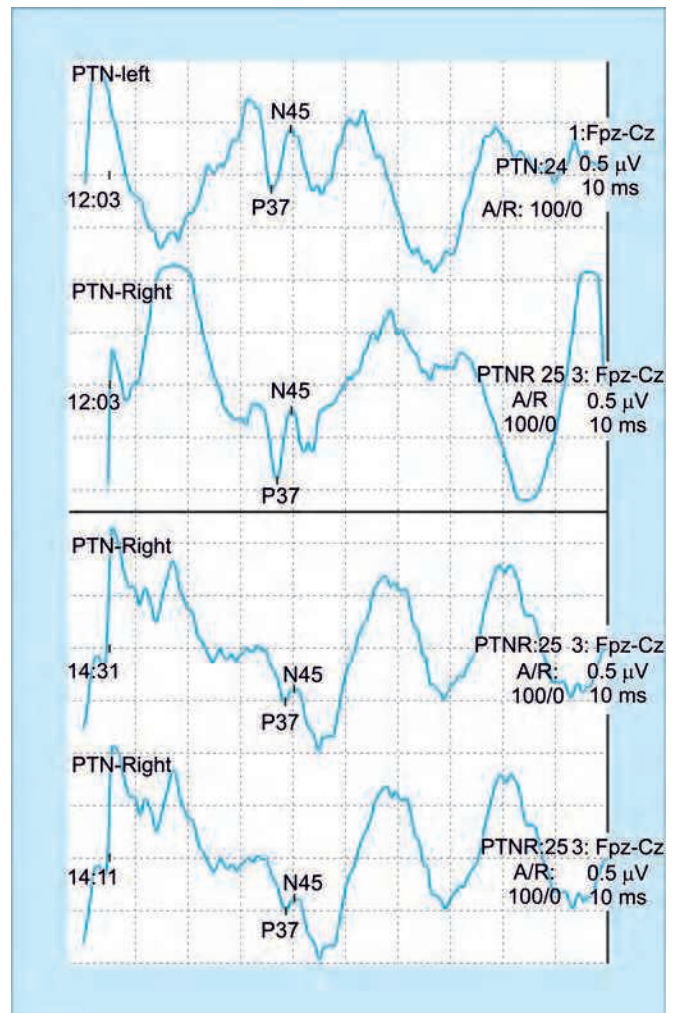


Fig. 127.2: Significant SSEP tracing change. Tracing 1 shows baseline SSEP. Tracing 2 shows the change after curve manipulation, showing a decrease in amplitude.

into the lateral and anterior funiculi of the spinal cord. Corticospinal tract axons that come from the premotor and motor cortex enter the spinal cord gray matter, interact with spinal interneurons, and subsequently synapse with alpha motor neurons that supply peripheral muscle. Motor-evoked potentials can be recorded either from the spinal cord (I and D waves) or directly from muscle producing a compound muscle action potential (CMAP).⁴⁴ Transcranial motor evoked potentials (TcMEPs) from the CST can be recorded from the spinal epidural or subdural space by a catheter-type electrode or from peripheral musculature (Fig. 127.4).

The “D-wave” is the response recorded from the epidural space and represents direct activation of the

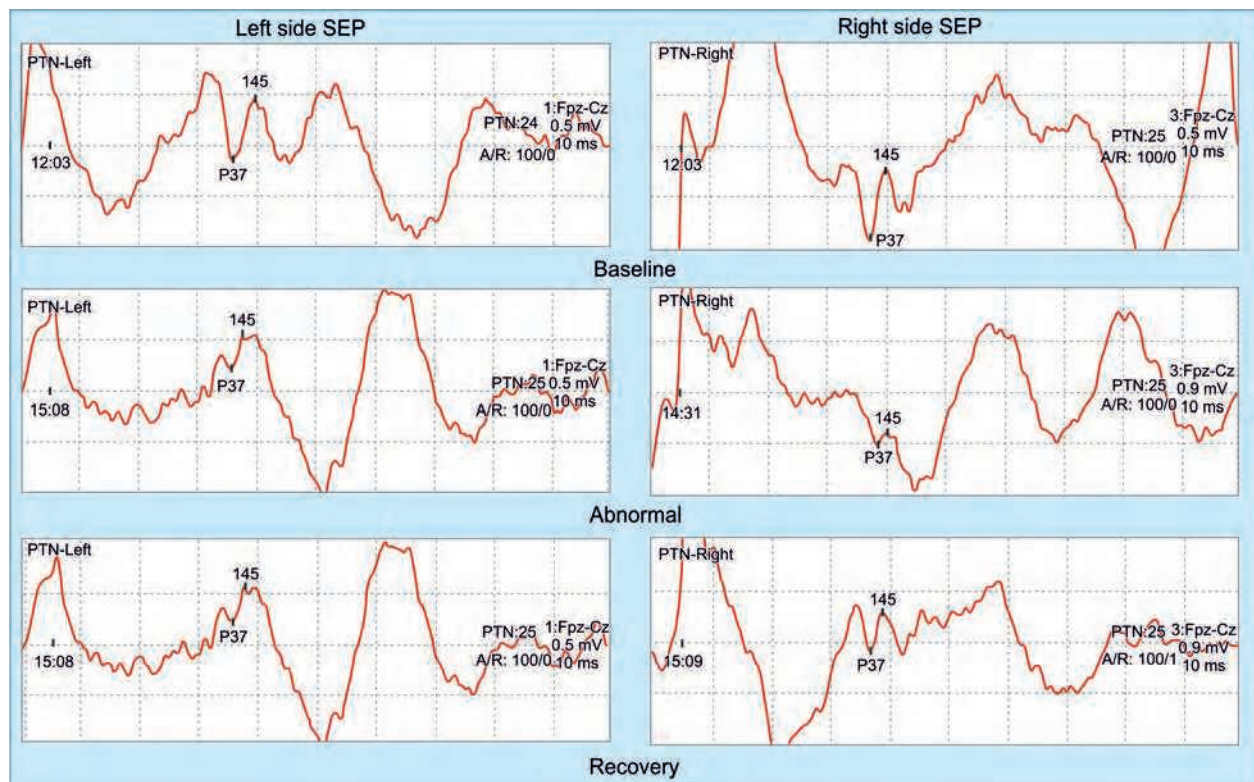


Fig. 127.3: The following tracings show baseline SEP tracings, followed by an abnormal tracing, with a decrease in amplitude, and eventual recovery (increase in amplitude) after correction.

CST cells. In awake or lightly anesthetized patients, the “D-wave” is followed by a series of “I-waves” that is generated indirectly by cortical synapses. These descending stimuli excite anterior horn cells and spinal alpha motor neurons, inducing a CMAP. However, setup is technically demanding because electrode placement is required, done percutaneously or through a laminotomy procedure. In addition, D-waves reflect global CST function that poses a difficulty in monitoring the cervical spinal cord because it might miss a selective injury to the cervical cord motor fibers that spares the lower extremity fibers. Therefore, it is both easier and preferable to record myogenic motor responses (CMAP) from upper (control) and lower extremity peripheral muscle.⁴⁴ CMAPs may be recorded from surface electrodes or subdermal needle electrodes placed over key peripheral muscles (Fig. 127.5).

Different alarm criteria for muscle MEP have been used, including all-or-nothing, amplitude, stimulation threshold, and morphology. The warning criterion is typically a 75% or more decrease in CMAP amplitude though individual differences should be considered.⁴⁴ In our institution, alarm criteria for MEP include the loss of 65%

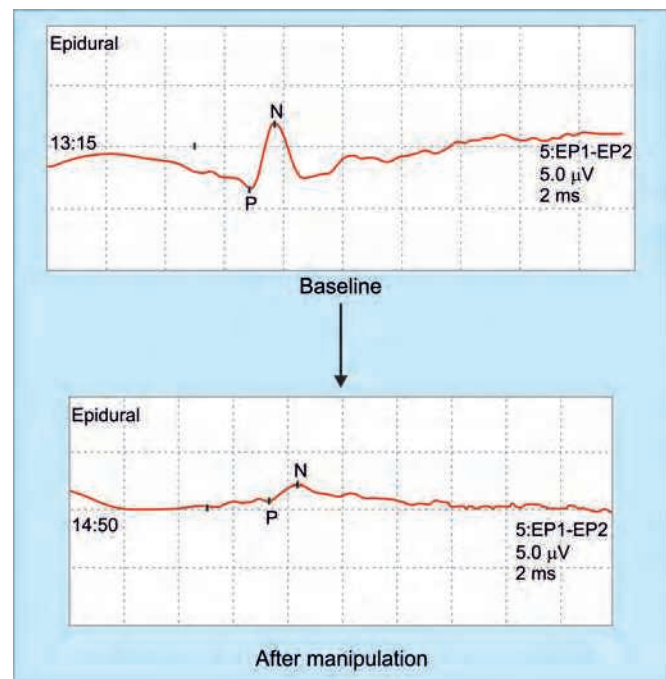


Fig. 127.4: Motor-evoked potentials. Tracing 1 shows baseline, while tracing 2 shows a decrease in amplitude after manipulation.

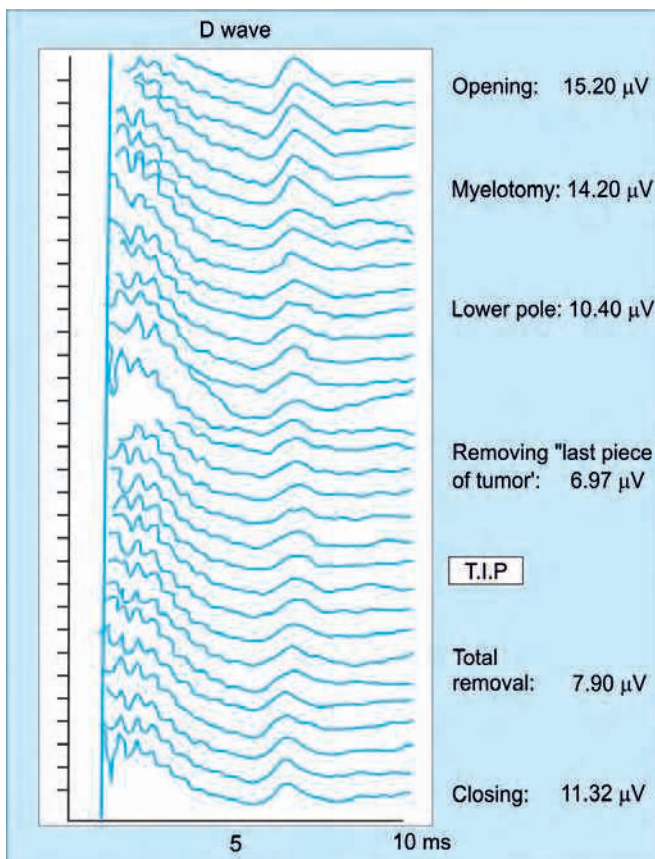


Fig. 127.5: Spinal cord evoked potential (D-wave).

amplitude and increase in 10% latency.¹³ Complete loss of muscle MEP with at least 50% preservation of D-wave can result to transient paraplegia, whereas complete loss of D-wave amplitude during surgery is likely to have permanent motor deficit (Fig. 127.6).

Limitations of MEP include the following. Setup is technically demanding and is not a continuous measurement. Signal can be absent in up to 40% of myelopathy patients. It is contraindicated in deep brain stimulators or cochlear implants. It also cannot be applied for surgery caudal to T10 since it cannot recruit enough axons to generate D-wave with sufficient amplitude for monitoring. Neuromuscular relaxation causes changes in TcMEPs; thus, muscle relaxants should be avoided during critical parts of surgery, however can be used during low-risk portions of the procedure such as during spinal exposure. Motor-evoked potentials are greatly affected by inhalational anesthetics and total intravenous anesthesia for reliable recording is more optimal.^{3,44} Chemical paralysis will prevent elicitation of MEPs.⁴⁴ Other factors that affect

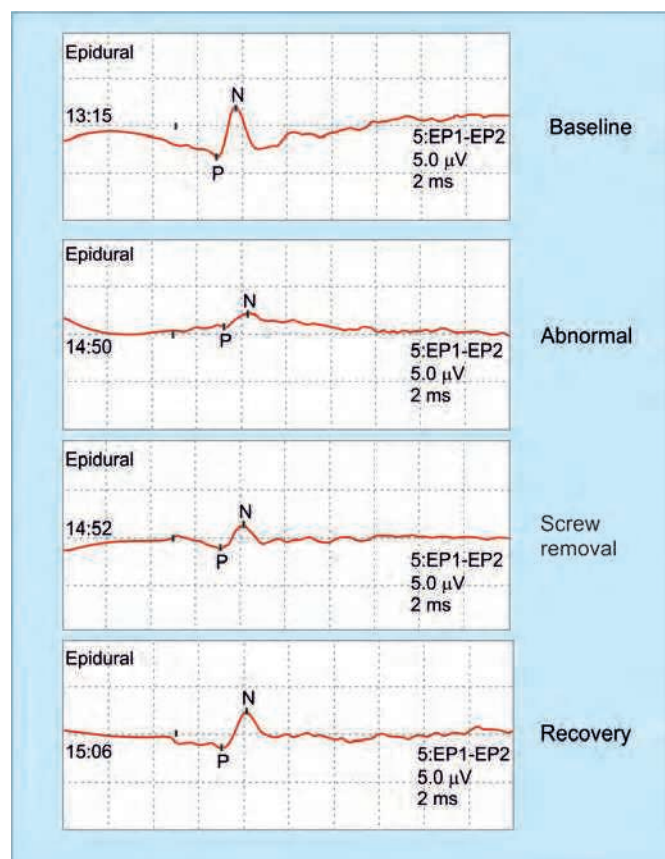


Fig. 127.6: Significant MEP (motor-evoked potential) changes. The first tracing shows baseline (normal) MEP signals. The second tracing shows a decrease in MEP signal, when the screw was inserted. The third tracing was taken during screw removal, showing an increase in the amplitude. The last tracing shows the recovery of MEP signals.

MEP include severe myelopathy, temperature, hypotension, and patient's height. D-wave [spinal evoked potential (SpEP)] is less sensitive to anesthetic agents. Both sensitivity and specificity in detecting injury are high as 100% and 95%, respectively.

Despite its technical setup complexity, TcMEPs are safe and effective in evaluating spinal cord motor tract function. Schwartz⁴⁰ reported on the safety of the procedure even in patients with cardiac disease, pace makers, and history of epilepsy. However, the most notable pitfall was the risk for tongue bite during cortical stimulation that causes severe jaw musculature contraction in patients without neuromuscular blockage.

An alternative to motor cortex stimulation is neurogenic motor-evoked potential (NMEP) that directly stimulates the spinal cord; however, it remains as an adjunct to

SSEP in monitoring sensory pathways.³ This is elicited by transosseous (spinous process, lamina) or epidural electrospinal stimulation and recorded over lower extremity peripheral nerves (e.g. popliteal fossae). Although initially, it was thought to be mediated within spinal motor tracts, researches have confirmed that both the neurogenic-evoked response and SSEPs are mediated through common spinal cord pathways; thus, it has remained as an adjunct to SSEP monitoring.³ Its advantages include technical simplicity in stimulation and recording, and are minimally affected by most anesthetic agents, including neuromuscular blockade. A neurogenic response is not a motor-evoked potential, but rather, represents antidromic spinal cord somatosensory activity. This has been confirmed in clinical practice by successful recording of NSEPs in paraplegic patients showing that this response does not depend on functionally intact motor tracts.⁴⁴ During occasions where SSEP, TcMEP, or H-reflex is difficult to elicit, epidural stimulation at the rostral thoracic level elicits a descending sensory potential that is recordable over the popliteal fossae.⁴⁴

The NMEP signal loss has been reported to occur before any corrective maneuvers and as late as 70 minutes after correction of kyphosis.⁵⁰ Causes of NMEP data loss include vascular insufficiency, overcorrection of the deformity, a combination of mild hypotension and overcorrection, and instability causing subluxation, laminar impingement or cord buckling. During deformity correction, the distraction forces stretch the anterior spinal artery leading to loss of intraoperative data. The relatively prompt return of neuromonitoring signals by releasing the correction supports this vascular theory. Temporary stabilizing rods before completing osteotomy can prevent neurologic deficit brought by abrupt instability of the spinal columns. Restoring anterior height restrains excessive shortening. The NMEP signal loss is reversed after suitable maneuvers stressing the importance of timely appropriate intervention.

Electromyographic Techniques

Electromyographic (EMG) technique is advantageous in identification of a specific nerve root injury, allowing early detection of excessive nerve-root traction, mechanical injury, or cortical breach. Intraoperative-evoked EMG monitoring of pedicle screw has been demonstrated to be a simple, safe, and efficacious technique in accurate placement of pedicle screws.⁵¹ Mechanically elicited EMG, also

called spontaneous EMG (spEMG), may be beneficial during the critical phases of surgery (during implant placement, nerve root manipulation), while electrically elicited EMG, also called stimulus-evoked EMG (stEMG) or triggered EMG (trEMG), may be useful during static phases of surgery.⁴⁴ The stEMG principle for identifying cortical breach resulting from placement of pedicle screws is based on resistivity of the different tissues to the flow of electric current. Cortical bone has a high resistivity (low conductivity) to electrical current flow, whereas soft tissue has a low electrical resistivity.⁵² The tip of a monopolar probe is touched to the screw shank or hexagonal port, and the electrical current output is increased by an electrical triggering device. In an intact cortical wall, there is high resistance; however, cortical perforation results to decreased resistance and the flow of electrical current will take the path of least resistance, which is through the breach to the root. As a result, the nerve root will depolarize at a much lower current (<7.0 mA) compared with an intact pedicle (10–12 mA). Subsequently, the root will fire and the peripherally innervated muscle will contract, and this will be recorded as a CMAP.⁴⁴ A positive EMG response at or below a constant-current of <6–10 mA may be an indication for inspection, redirection, or removal of the instrument or implant (Fig. 127.7).⁵¹

Thoracic pedicle screw stimulation is more difficult than lumbar screws; furthermore, T1–6 monitoring results may not be reliable. An abnormal EMG response during a spine procedure may or may not be associated with a clinical deficit,⁵³ while on the contrary, normal EMG response does not insure against lateral breeches. Another limitation is its use in chronically compressed roots. Having an elevated threshold, long-standing motor nerve root compressions will not fire spontaneously or will result in false-positive tests in stEMG techniques. A quiet spEMG of a chronically compressed nerve root does not translate that the root is “safe.” Chronically compressed nerve roots show altered thresholds; thus, must serve as their own control to establish a safe trEMG threshold.⁴⁴ Metabolic conditions, such as diabetes, can also affect outcome results. Paralytic agents cause neuromuscular junction blockade thus producing false-negative results.

Multimodality Monitoring

Different monitoring technique has its own advantage and limitations, one technique alone will not be able to meet

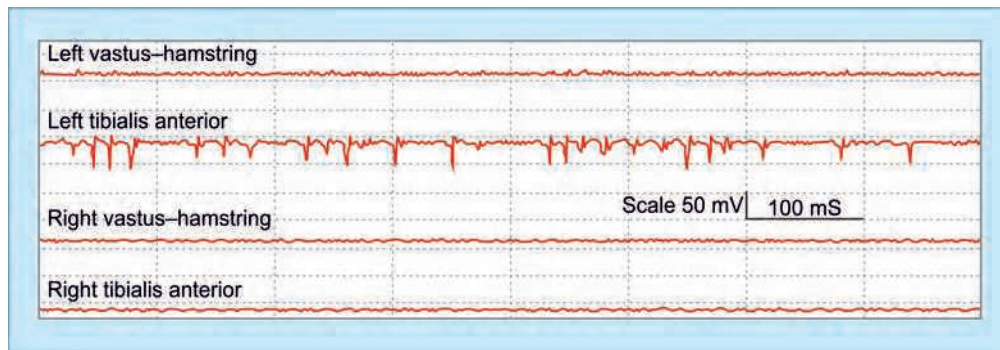


Fig. 127.7: Electromyographic monitoring.

all monitoring needs. No single monitoring technique can assess both motor and sensory pathways; therefore, multimodal spinal cord monitoring has been proposed to improve monitoring reliability and validity.⁵⁴ The utility of multimodality monitoring is stressed and should be considered a standard of care during spinal surgery.²⁸

In the retrospective review of Pastorelli⁵⁵ with 172 spinal deformity patients using intraoperative monitoring either with SEPs alone or combined with TES-MEP showed an overall prevalence of postoperative neurologic deficit of 2.3%. When combined SEP and TES-MEP monitoring were performed, the sensitivity and specificity of neurologic monitoring for sensory-motor impairment was 100% and 98%, respectively. They recommended that combined SEP and TES-MEP monitoring must be regarded as the neurophysiological standard for intraoperative detection of emerging spinal cord injury during corrective spinal deformity surgery. Early detection affords the surgical team an opportunity to perform rapid intervention to prevent injury progression or possibly to reverse impending neurologic sequelae. In cervical spine surgery, the sensitivity and specificity for detecting evolving motor tract injury with TcMEP was 100% compared to 25% sensitivity and 100% specificity with SSEP.⁵⁶

Luk³⁷ did a prospective study comparing the outcomes of different-evoked potential techniques for intraoperative spinal cord monitoring. They compared cortical somatosensory-evoked potentials (CSEP), cortical motor-evoked potentials (CMEP), spinal somatosensory-evoked potential (SpSEP), and spinal cord-evoked potential (SpCEP) on 30 patients. Their results did not demonstrate significant variability in the latencies of each technique however amplitudes showed significant differences between different techniques. Cortical somatosensory-evoked potential was more variable but easy to use, economical, and

noninvasive. Spinal somatosensory-evoked potential is easily interrupted by surgical procedures and loading of spinal instrumentation but is also the most stable and reproducible technique, rarely influenced by anesthesia, and capable of producing relatively large amplitudes for monitoring. Cortical motor-evoked potential is reliable and stable with large amplitudes and easily recognizable waveforms but is difficult to elicit from scalp stimulation. Spinal cord-evoked potential, though easily detected with good signal, monitoring is easily interrupted by surgical procedures. The four techniques complement each other. The study recommends that CSEP and CMEP should be recorded first to assess the waveforms quality. If CSEP and CMEP waveforms obtained are clear and large, then SpSEP and SpCEP are not necessary. Spinal somatosensory-evoked potential or SpCEP can be used as substitutes for CSEP and CMEP, respectively. Spinal cord-evoked potential and CMEP had clearer waveforms of greater amplitude allowing faster detection than CSEP and SpSEP waveforms. Furthermore, SpCEP and SpSEP waveforms were more easily influenced by the surgical procedure. Their conclusion was CSEP and CMEP are recommended for routine monitoring so that both ascending and descending tracts are monitored. If signals are not easily obtained, SpSEP can be substituted for CSEP while SpCEP can substitute for CMEP.

Schwartz⁴⁰ investigated the advantage of monitoring the spinal cord motor tracts directly by recording TcMEP along with SSEP. They concluded that TcMEP are highly sensitive to alterations in spinal cord perfusion either from hypotension or a vascular insult. In addition, changes in TcMEP are detected earlier than changes in SSEP, enabling a more rapid identification of impending spinal cord injury. This has been supported by Vitale et al.²⁰ and recommends combined SSEP and MEP allowing early detection of spinal cord dysfunction in most patients.

A 23-year retrospective study of 3,436 consecutive pediatric orthopedic spinal surgery patients⁵⁷ reviewed different monitoring techniques, including SSEP, descending neurogenic-evoked potentials, TcMEP, and various nerve root monitoring techniques. The combined use of SSEP, TcMEP, descending neurogenic-evoked potentials and EMG monitoring allowed accurate detection of permanent neurologic status in 99.6% and reduced the total number of permanent neurologic injuries to 6 out of 3,436 cases. Combined SSEP and MEP monitoring effectively prevents neurologic injury in most children undergoing surgery for spinal deformity.

It has been reported that NMEPs provide an early warning of impending neurologic deficit well before SSEPs have changed. Thus, it is imperative in these high-risk kyphotic correction cases to have a combination of multimodality and neurologic spinal cord monitoring including some type of motor tract monitoring. Somatosensory-evoked potential data did not change before the loss of NMEP data. Thus, using SSEPs alone, even with a wake-up test, may not provide the early warning necessary to avoid a real neurologic deficit after surgery.⁵⁰

Latencies and amplitudes of SEP in the different stages of scoliosis surgery were compared by Luk et al.,³⁸ showing that the latency values and their percentage variabilities did not significantly differ from each other in different stages of surgery. However, the amplitudes between different stages of surgery showed a statistically significant difference, particularly the decrease in amplitude between preoperation (stage 1) and spine exposure (stage 2). This study shows that there is some variability in the latencies and amplitudes between different stages of scoliosis surgery though still within normal range. Using the decreased amplitude in stage 2 (spine exposure), when there is no risk in injuring the spinal cord mechanically, there were no false-positive readings. This lower amplitude at stage 2 can be used as reference baseline to determine whether SSEP are subnormal at the subsequent stages of surgery and may be a more reliable baseline for monitoring. The difference in amplitude can be attributed to the decrease in the core body temperature and the spinal cord that occurs while the spine was exposed. This can be reversed by warm irrigation of the wound.

It is imperative to determine the baseline in relation to the normal variability to improve the reliability of the intraoperative SEP monitoring.⁵⁸ It is recommended to have a low threshold for defining relevant electrophysiological changes despite the potential for false-positive

results. Rapid intervention can reverse these changes and avoid potentially serious neurologic complications.²⁰

Stagnara Wake-up Test

First described in 1973, this test is used to assess the neurologic function intraoperatively.⁵⁹ The wake-up test is performed after the desired correction has been achieved with temporary reversal of general anesthesia, after which the patient is asked to move the upper and lower extremities. A positive wake-up test was defined when voluntary movement of one or both lower limbs was NOT observed with normal upper extremity function, while a wake-up test is negative when the patient demonstrates normal motor function from all four extremities on command.⁵⁷ It is important to counsel the patient before surgery that she will be asked to move her lower limbs during surgery.

This test interrupts the surgical procedure to allow for the awakening, which is time-consuming and cannot be performed repeatedly during the operation. Therefore, the exact moment when trauma was incurred remains uncertain; it may have been performed long after the injury to the cord.³⁸ This global assessment of the spinal cord function does not provide accurate data concerning subtle weakness, timing or location of the neurologic injury. An early neurologic injury presenting only as motor weakness can also be missed because it is not possible to obtain a true motor strength examination.³⁵ This test should be reserved for patients who are able to understand and follow specific commands and has limited use in patients with intellectual and developmental disability and young age, as they have difficulty following commands and in those with language barriers.^{55,60} It is inappropriate in patients with preoperative weakness because assessment will not be accurate. Other risks in performing this procedure include self-extubation, loss of intravenous access, loss of safe patient positioning on the table, air embolism, and postoperative recollection of event.⁶⁰

The most significant shortcoming of the wake-up test is that it is done at a single time during surgery which is after correction. It assumes then that spinal cord injury cannot occur at any time during surgery. The temporal delay in detecting injury from the time of insult is significant because identification of the particular maneuver, causing the injury is not possible. Therefore, timely intervention is delayed and injury may not be reversible. Manifestation of the injury is not time-locked and may present itself at any time, even after wake-up test is performed.^{40,61}

MANAGEMENT OF INTRAOPERATIVE NEUROLOGIC LOSS

Preoperative Preparation

Risk for neurologic injury starts even before surgery and the surgeon should be well-prepared every step of the way. A thorough understanding of anatomy minimizes direct injury to the neural elements. The pedicle is a constant anatomical landmark for the exiting nerve root, which is located inferomedial to it. The conus medullaris terminates between L1 and L2 in adults; injuries to this may cause bowel, bladder or sexual dysfunction. Normal anatomic variations should be recognized in preoperative studies to modify approach. The incidence of conjoined nerve roots is between 2% and 14%. In approaching the lumbar spine anteriorly, particularly in approaching the L5/S1, be mindful of the hypogastric nerve plexus and sympathetic chain. The hypogastric plexus innervates the seminal vesicles and the vas deferens in males, traumatizing these results into retrograde ejaculation. Injury to the sympathetic chain on the anterior surface of the psoas can cause contralateral foot coldness and increased in warmth on the ipsilateral foot.

The patient's clinical condition is another factor to consider when choosing the surgical approach. It has been reported that the risk of dural disruption in multilevel cervical OPLL is higher in the anterior approach versus the posterior approach. Posterior approach is therefore suggested in this condition provided having a lordotic cervical spine or flexible kyphosis.⁶² Anterior decompression for cervical myelopathy was found to have an incidence of 3.2%,⁶³ and as high as 6.7%⁶⁴ for postoperative C5 radiculopathy. C5 palsy is manifested by paresis of the deltoid and/or biceps brachii muscle, sensory deficits, and/or intractable pain in the shoulders.⁶⁴ Saunders⁶⁵ identified several risk factors after cervical corpectomies, including moderate-to-severe myelopathy, age >60 years, kyphosis, and a wider corpectomy decompression. Functional recovery is generally good, but severely paralyzed cases (MMT ≤ 2 or less) require significant longer recovery time compared to mild cases.⁶⁶

Anterior approach to the lumbar spine is advantageous because it allows direct access to ventral pathology, spares lumbar paraspinal musculature improving postoperative mobility and decreases chronic muscle pain, avoids previous posterior surgical scars, and enables anterior placement of interbody grafts and devices.^{2,67} Posterior lumbar

interbody fusion and transforaminal lumbar interbody fusion allow improved segmental and coronal correction and provide anterior column support, while allowing indirect foraminal decompression and with greater surface area for arthrodesis. However, approach-related neural injury includes trauma to the exiting or traversing nerve root while accessing the intervertebral space.¹

Preoperative discussion with the anesthesiologist in patients with special considerations facilitates patient care. The anesthesiologists can anticipate special procedures such as deformity correction, wake-up tests, and the use of intraoperative monitoring. Halogenated anesthetics affect SSEPs but have little effect on spinal SEPs.⁶⁸ Spinal SEPs are affected by temperature and local anesthetic agents, while cortical SEPs are affected by inhalational and induction agents, local anesthetics, and opioids. However, MEPs are sensitive to inhalational drugs.⁶⁹ Adequate intravenous access should be available and central venous access as well as arterial line to monitor the mean arterial blood pressure are suggested. Consider using fiber optic intubation in patients with severe cervical stenosis to avoid excessive neck manipulation.⁷⁰ Special care should be observed during positioning in patients with high-grade lumbar or cervical stenosis to avoid neurologic injury. Document the preoperative range of motion in cervical spondylotic myelopathy patients. Patient with cervical stenosis should be transferred with the neck in neutral or slightly flexed position. Keep the abdomen free to minimize intraoperative blood loss when positioning the patient prone. Peripheral nerves are at risk for injury during anterior cervical spine surgery from traction or direct pressure on the brachial plexus or ulnar nerve during intraoperative positioning. Keep the extremities well padded. Leads for intraoperative neurologic monitoring should be placed and secured before positioning the patient.

Suffice it to say that to decrease the risk of injury to neural elements, adequate exposure is needed without removing bone excessively that could lead to iatrogenic instability. In using sharp instruments, such as the pituitary rongeur or the burr, be mindful of the neural structures to avoid direct injury. Careful retraction of neural elements after the dura has been freed should be observed, avoiding manipulation of the thecal sac above L2. When removing the flavum, avoid tearing or ripping from the dura. Meticulous hemostasis should be practiced by using bone wax and hemostatic agents, and using drains as needed.

During surgery, it is imperative to maintain adequate mean arterial pressure (MAP > 70–80 mm Hg) to preserve

adequate spinal cord perfusion. It has been demonstrated that spinal cord ischemia may result from prolonged extreme hypotension (MAP < 55 mm Hg), hypoxia secondary to decreased hemoglobin level, or vascular compromise after ligation of segmental vessels in an anterior procedure.⁷ Ideally, the MAP should be maintained at 65–70 mm Hg during exposure and placement of instrumentation.⁴⁰ Inform the anesthesiologist before doing corrective maneuvers to gradually elevate the MAP > 70 mm Hg to maintain cord perfusion during the spinal manipulation and correction.³⁵

Instrumentation should be placed with utmost care and deformity corrected using precise techniques. Malpositioned screws, apart from neuronal injury and pain syndrome, can induce loss of fixation.³ Use of osseous landmark guides the proper starting point in pedicle screw insertion or directly palpates the pedicle through a laminotomy in severe deformity. Inspect for inadvertent perforations, after creating the screw track and after tapping. Radiography or fluoroscopy should be used to assess screw placement and overall alignment after insertion of hardware. Neural elements should be protected during interbody preparation and interbody implant placement. Posterior interbody grafts or cages used in lumbar interbody fusions can displace and encroach on the nerve roots or cauda equina. During posterior lumbar procedures, the wide exposure required for graft insertion increases the risk to traction injury or development of instability.³⁶

Using multimodality spinal cord monitoring decreases the rate of major neurologic deficit by alarming the surgeon of neurologic injury or impending injury so remedial action can be performed to reverse the trauma. Using intraoperative neurologic monitoring such as TcMEP and SSEP appears to be prudent for procedures where there is significant risk of injury to neural structures and in high-risk patients.³⁹ Somatosensory-evoked potential and/or MEP signals must be continuously monitored during surgery, instrumentation, and deformity correction. Once changes are observed, the surgeon must be alerted, and immediate action is imperative. Generally, neural injury is suspected when there is change of >50% amplitude and >10% latency in the SSEP and/or MEP signals. The combined monitoring of sensory-evoked potentials and MEPs during spine surgery decreases the false-negative rates of reporting. Combining MEP monitoring with SSEP in spine surgery⁷¹ is advantageous because more patients can be monitored. Accuracy is increased by complementary

information from two independent systems reducing the risk of false-negative results, and increasing sensitivity in identifying early spinal cord dysfunction.

Once the surgeon is alerted of signal change, he should halt the surgery and investigate the reason for the significant change in signal, undertaking a structured and fairly logical procedure. First determine if there is any technical problem or equipment malfunction. Check the leads and connections that they are secured and in proper position. Stimulation limits might have to be changed and electrodes repositioned. Adjust patient positioning and relieve vena cava pressure. Next, verify anesthetic concentrations with the anesthesia personnel, along with blood loss and mean arterial pressure.⁵⁷ Physiologic factors such as anemia and hypotension, which greatly affect spinal cord perfusion, should be corrected. Optimize the hemodynamic status of the patient (elevate MAP > 80 mm Hg or 20% above baseline values) to improve perfusion pressure to the spinal cord.^{40,72} Most false-positive TcMEP changes occur when the mean systolic blood pressure is too low, thus keeping the mean >80 mm Hg is necessary to eliminate false-positive results. Hypertension might have to be induced to increase MAP, and to do so, the anesthesiologist should start a dopamine drip to raise the MAP. It has been suggested that optimizing hemodynamic conditions should be done before unloading the distraction because mechanical factors (e.g. distraction-induced vasoconstriction, increased spinal cord interstitial pressure) and suboptimal hemodynamic conditions when combined can alter the MEPs.³¹ Furthermore, ensure that the patient's temperature is > 36.5°C (97.7°F) to optimize neuromonitoring. Irrigate the wound with warm saline. Investigate the glucose levels. Other factors to check would include retractor positions and removing intradural packings and explore the wound for direct injuries to the neural elements. Reassess signals after every step because this aids in accurately identifying the possible inciting factor. A wake-up test is recommended to assess the spinal cord function if there is any doubt or with increased risk of postoperative neurological deficits.^{38,73} When suspected spinal cord injury (SCI) occurs, radiographic and/or direct examination of bone graft and hardware should be conducted to confirm the lack of direct spinal cord compression.⁷⁴

The role of steroids remains to be controversial.⁷⁵ Steroids could be administered to patients who have a continued negative wake-up test (absence of motor function) after the release of tension from corrective and distractive

maneuvers.^{40,60} Consider using high-dose methylprednisolone or intravenous dexamethasone.^{4,60,76}

The release of tension or degree of correction should be contemplated if the previously mentioned factors have been looked into and fairly rectified without any signal return. Set screws are loosened and the rod may be removed to lessen the correction. Early removal of instrumentation may increase the possibility of neurologic improvement⁷⁷; however, the stability of the spine has to be ensured to avoid subluxation of the spinal column when the rod is removed. If the removal of instrumentation weakens the stability of the spinal column (i.e. vertebral body resection), the surgeon may be obliged to maintain the existing instrumentation and fuse the spine under the least amount of tension.⁶⁰ The signals are checked promptly after each maneuver, and once the signals return, correction can be sustained by fusing it in situ or one with a lesser correction, or attempt a more modest correction.⁷⁷ Return to baseline of the evoked potentials should be demonstrated before more reduction is attempted. It is also essential to assess for any impingement that would require a more thorough decompression before the repeating any attempts in correction. If signals improved following surgical intervention, no further action was taken. The Stagnara test was used when signals remained degraded despite intervention, or when no apparent cause-effect relationship for the signal loss was found within the surgical procedure.³¹

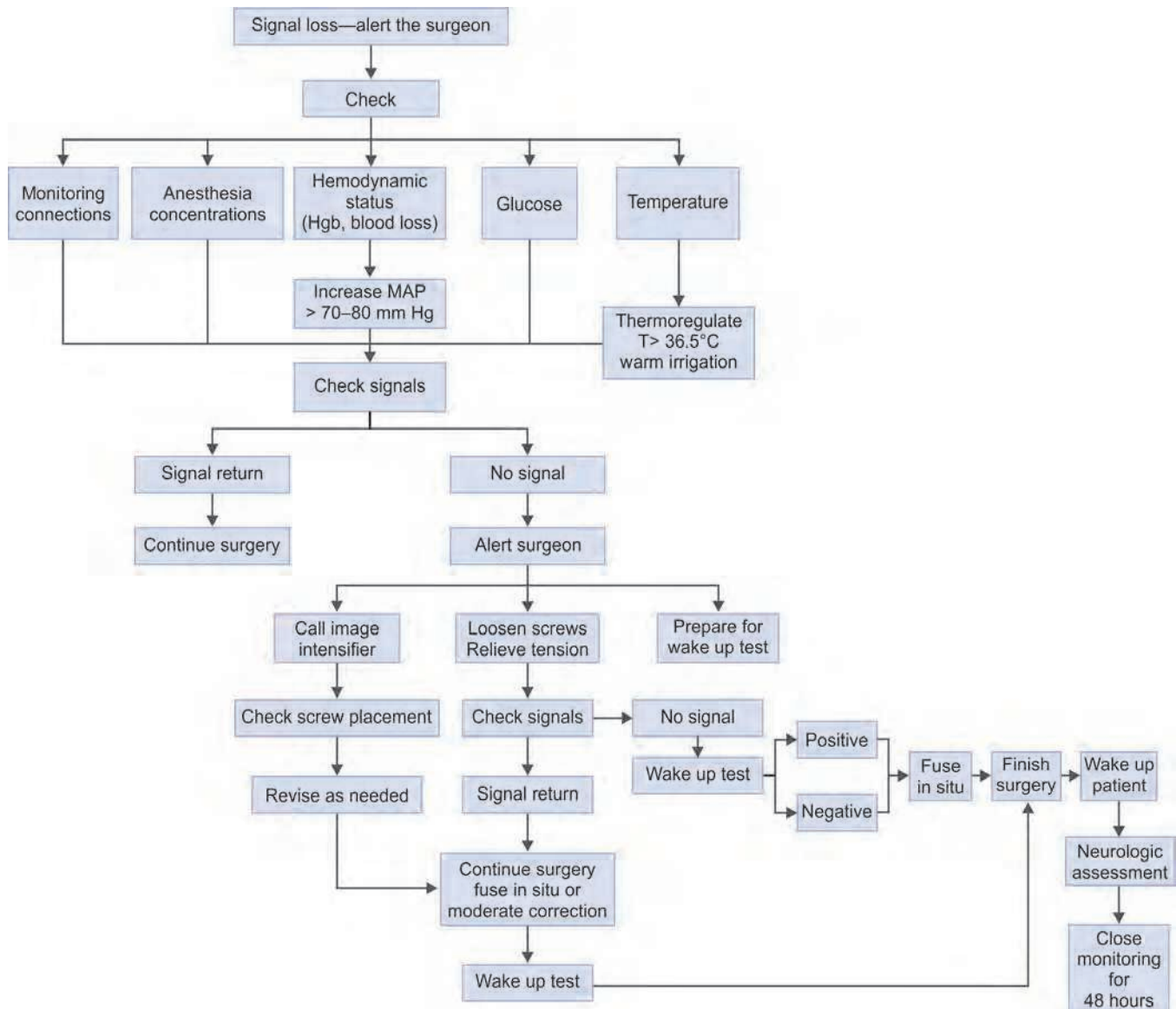
In a report of 275 consecutive patients treated with posterior spinal instrumentation and fusion with intraoperative neuromonitoring (IONM) using SSEP, patients who exhibited significant evoked potentials changes during instrumentation showed return to baseline with immediate removal of the instrumentation with all patients neurologically normal postoperatively.⁷⁸ Similar results have been reported demonstrating no subsequent neurologic deficit after revision of the operative procedure when evoked potentials changed.^{3,79} Another report demonstrated that interventions caused by IONM change reduced true-positive outcomes from 3.1% of those with signal change to 0.12%.²⁸ Therefore, one can surmise that changes in cord function can be reversed when the cause is quickly remedied.³

Pedicle screw malposition was the most commonly identified problem according to a report by Raynor et al.²⁸ Therefore, pedicle screw position should also be closely examined in monitoring change, using image intensifier and removing suspicious screws, and verifying the integrity

of the track by direct palpation using a ball tipped probe. A pedicle screw tip that is past the midline of the vertebral body on PA radiographs suggests a medial pedicle breach.⁸⁰ A small laminotomy may also be performed to evaluate the integrity of the medial pedicle cortex with or without screw removal.⁴ An EMG may be also be used to investigate pedicle wall breach. Any pedicle screw with markedly lower EMG threshold (<60%) compared to the rest of the construct should be assessed because this may indicate a possible pedicle wall breach.⁸¹ A stimulation threshold >15 mA reliably indicates adequate screw position while stimulation threshold between 10 and 15 mA, generally associated with adequate screw position, exploration of the pedicle is recommended. A stimulation threshold <10 mA was associated with a significant cortical perforation in most instances.⁵¹ If there is any breach or malposition, screws are reinserted and position verified using imaging techniques (Flowchart 127.1).

The spinal cord should not be retracted during surgery. Spinal cord tissue is much less tolerant to traction and compression than nerve roots; therefore, even minimal manipulation of the cord may cause profound neurologic consequences. Moreover, the spinal nerve roots are less tolerant to mechanical deformation compared to peripheral nerves. The intradural nerve rootlets are covered by a thin sheath that is permeable to cerebrospinal fluid for nutrition,⁸² while peripheral nerves are protected by epineurium and perineurium making them less susceptible to injury. Traction can substantially reduce nerve root blood flow, causing ischemic nerve root injury resulting in nerve dysfunction.⁸³ Decreased retraction time and tension leads to lower the rate of ischemic injury.

Dural tears, one of the most common iatrogenic injuries, may occur during any spinal procedure in which the dura is decompressed, manipulated, or brought into contact with the surgical instruments. The incidence of dural tear during anterior cervical spine surgery has been reported to range between 2% and 14%.¹ Revision interbody fusion procedures have a higher minor perioperative complication rate, particularly dural tears, than primary procedures.⁸⁴ To avoid dural tears, removal of the ligamentum flavum should be done with utmost care with proper instruments. Direct repair with suture or placement of fibrin glue or other sealant is recommended to prevent persistent CSF leakage and increased risk of meningitis and pseudomeningocele formation.¹ Chang⁸⁵ demonstrated

Flowchart 127.1: Algorithm for intraoperative neurologic loss.

the formation of syrinx when CSF flow in the subarachnoid space was obstructed. There is increase in spinal cord pressure distal to the blockage, and this location corresponded to the preferred site of syrinx formation in adhesive arachnoiditis. He further suggests that surgical procedures, such as shunting, be performed to reduce this pressure gradient. A Valsalva maneuver aids in the identification of a persistent or residual leak. If there is a persistent leak, reinforce repair with muscle or fat grafts sutured over the repair to the dura. Larger defects may require patch grafting with a segment of fascia from the paravertebral muscles.³⁶ Watertight

closure without wound drains is required. Durotomies that occur during minimally invasive procedures are difficult because of the limited exposure and one may have to convert to open techniques to allow repair. Postoperative management of dural tears includes 24–48 hours of bed rest to reduce pressure and allow dural healing. Antibiotics are given to reduce the risk of meningitis. Lumbar drains can be considered in repairs that are doubtful. To reduce intraspinal CSF following surgery, upright patient positioning in the cervical spine, while recumbent positioning is suggested if the leak was in the lumbar region.

Recognizing the cause of IOM signal degradation is critical because it leads to timely use of appropriate and effective intervention. There was good correlation exists between problem recognition, intervention, and data improvement, with intervention leading to signal improvement as a strong indication for a favorable neurologic outcome.³¹

Postoperative Care and Detection of Deficit

Once the patient is awake, immediate evaluation of the neurologic status is warranted before leaving the operating room. Frequent neurological examinations in the first 48 hours after surgery are highly recommended. Postoperative evaluation of patients with new neurologic deficits should include an emergent MRI or CT myelogram to evaluate for neurologic injury and to rule out hematoma or misplaced graft or hardware.¹¹ In patients with postoperative neurologic deficits or leg pain after placement of instrumentation, CT scan is the imaging modality of choice because it accurately demonstrates screw placement. Unsatisfactory screw placement in the setting of new onset leg pain or neurologic deficit is best managed by reoperation to remove or replace the device and to ensure adequate neural foraminal decompression.³⁶

Early postoperative deficit (1–14 days) usually occurs secondary to retained disc fragments after discectomy, postoperative hematoma, pseudomeningocele, herniation of a fat graft or rarely an epidural abscess.³⁶ Early re-exploration is suggested if nerve palsy is complete; however, a more conservative management such as watchful waiting is done if palsy is incomplete. Serial examinations and electrodiagnostic studies at 1 and 3 months are done if deficit is persistent. If there are no signs of recovery at 3 months, explorations are also suggested.

KEY POINTS

- Low risk for neurologic injury in spine surgery but has great impact on patients.
- Preparation of both the patient and surgeon is imperative to decrease the risk of neurologic injury.
- Consider intraoperative monitoring, in particular multimodality intraoperative neurologic monitoring.
- Follow an algorithm in managing intraoperative neurologic loss and do appropriate and timely maneuvers to rectify and possibly reverse the deficit, preventing permanent injury.
- Postoperative monitoring is important since neurologic injury can still occur even after surgery.

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Complications of Anterior and Posterior Cervical Spine Surgery

Jason Pui Yin Cheung, Keith Dip Kei Luk

Snapshot

- » Overview
- » General Complications
- » Access Related
- » Decompression Related
- » Instrumentation/Implant Related
- » Fusion Related
- » Delayed or Late Complications: Postlaminectomy Kyphosis

OVERVIEW

Complications of anterior and posterior cervical spine surgery could be categorized as general, access related, decompression related, instrumentation related, fusion related and delayed or late complication of postlaminectomy kyphosis.¹ Avoidance of complications require good preparative planning such as having the correct indication for surgery, thorough assessment and preoperative preparation of the patient and acquiring all the necessary imaging, equipment (blood products, neurophysiological monitoring, anesthetic equipment), medical evaluation prior to surgery and adequate personnel familiar with different operating tools. Furthermore, ensuring that as a part of the surgical plan there is a “fall-back” option to which the surgeon can resort if intraoperative events are encountered is very helpful in ensuring a successful outcome.

GENERAL COMPLICATIONS

Anesthesia and Positioning

The incidence of postoperative respiratory compromise after multilevel anterior cervical decompression with or without posterior fusion was reported as 0–14%.^{2–5} Respiratory compromise is a result of upper airway edema due

to anterior soft-tissue trauma or if the patient is in prone position for too long.^{2,4} If the spinal cord is at risk due to instability, the neck muscles are unable to provide the necessary stabilization to protect the cord during manipulation when intubating. Undue force used during laryngoscopy and tracheal intubation may move the cervical vertebrae and jeopardize the spinal cord. In these cases, manual inline axial stabilization and fiberoptic endoscopy is necessary; however, the safest technique available is to perform an awake fiber-optic intubation while ensuring that the patient’s neurological examination remains unchanged.

Hypotensive anesthesia provides surgeons with an easier surgical exposure due to reduced blood loss. However, this blood pressure must be carefully controlled to avoid spinal cord ischemia. Spinal blood flow of at least 65% of baseline is required to maintain physiological integrity of the spinal cord and a 12% decrease in blood flow carries with it the potential for paralysis.^{6,7} Usually, a mean arterial pressure of 65 mm Hg, or 20 mm Hg below baseline in normotensive patients is safe in patients in whom their spinal cord is not otherwise at risk (compressed or manipulated).⁸ Adequate neural perfusion is particularly important in traumatic spinal cord injury due to an already compromised swollen spinal cord. Often, a mean arterial pressure of 85 mm Hg is necessary for perfusion.

Patient positioning is the first responsibility of the surgeon to provide easy surgical access and to prevent pressure areas at bony prominences and to avoid iatrogenic injuries. For posterior cervical approaches, the head and neck must be controlled during turning either by free-hand or via Halo ring or Mayfield tongs. Prone positioning may increase intraocular pressure leading to ischemia, decreased perfusion pressure and blood supply to the retina causing ischemic optic neuropathy and blindness. Injury to the eye can occur as a result of pressure due to the Mayfield headrest or Gardner Wells tongs. Shoulders are pulled distally to facilitate lateral X-ray of the cervical spine and are usually taped to the operating table. The shoulders should not be extended below the coracoid process to avoid brachial plexus compression. Neurological deficit can occur during improper positioning such as brachial plexus injury. Thus, the shoulder should not be abducted beyond 90°. In prone position, the shoulders should be flexed, internally rotated and minimally abducted to avoid thoracic outlet obstruction. The radial nerve may also be injured if the arm hangs over the edge of the operation table. Injury to the common peroneal nerve can occur if the lower extremities roll into abduction with external rotation. Pressure necrosis of skin over the sternum, breasts, iliac crests and knees is more common in prone positioning. Adequate padding under pressure points can prevent skin breakdown and peripheral nerve compression.

Bone Grafting

Up to 2.5% of iliac crest bone-grafting procedures have been associated with long-term harvest site pain (3 months).⁹ Superficial nerve injury following iliac crest bone-graft harvest is not commonly discussed but may occur more frequently than appreciated. Ilioinguinal neuralgia can occur from retraction of the abdominal wall where the nerve is pinched between the retractor and the iliac crest. With posterior iliac crest bone graft harvest, care must be exercised to prevent injury to the superior cluneal nerves, which cross just lateral to the posterior superior iliac spine and supply sensation to the superior two-thirds of the buttocks. Careful soft tissue handling such as reduced stripping of pelvic muscle or thigh musculotendinous attachments from anterior thigh muscles to the iliac crest, protection of sensory cutaneous nerves and less subperiosteal stripping can help reduce postoperative donor site pain. Poor donor site handling can lead to hematoma or seroma formation and subsequent infection but these complications can usually be treated by antibiotics alone.

Watertight closure of wounds can prevent fluid from entering the subcutaneous space thereby avoiding seroma formation. A deep drain should be used in expected deep hematoma formation to drain it and avoid infections. However, there is limited evidence for drain use as one prospective randomized study showed no differences in the occurrence of wound complications (10%) even with a suction drain.¹⁰

Anterior iliac crest bone graft harvest has risk of injury to the lateral femoral cutaneous or ilioinguinal nerves due to direct injury, retraction, fracture, or subfascial hematoma. Incisional hernia is a rare complication (0.5%) that occurs when bowel protrudes through the osseous defect in the ilium after an inadequate abdominal musculature closure.¹¹ Dissection limited to the outer table of the pelvis with minimization of abdominal and pelvic muscle attachment stripping can help prevent herniation. Avulsion fractures of the anterior superior iliac spine can occur after graft harvest is performed too far anteriorly along the crest and occurs with forceful contraction of the sartorius muscle and/or tensor fasciae latae. In order to reduce the risk of this complication, many authors have recommended that the anterior iliac crest harvest site should be >3 cm posterior to the anterior superior iliac spine.^{9,12,13} Avulsion has been shown to be more frequent with bicortical and tricortical anterior superior iliac spine grafts than with unicortical grafts.¹²

The superior gluteal artery is the most common vascular injury associated with posterior iliac crest bone graft harvesting and is usually injured by a dislodged retractor or osteotome. After transection, the superior gluteal artery frequently retracts into its intrapelvic position behind the sacrosclatic notch and is difficult to approach posteriorly without removing bone from the notch. Direct ligation hence requires turning the patient supine and for exploration through an anterior retroperitoneal approach, or more commonly an urgent trip to the angiography suite where embolization can control the bleeding. Ligation and embolization do not carry significant sequelae such as muscle necrosis or ischemia due to good collateral anastomosis. Prevention of injury requires careful assessment of the safety boundaries. Caudal limit of harvesting should be the inferior margin of the origin of the gluteus maximus at the area of the posterosuperior iliac spine. Retractor placement in the sciatic notch should be avoided and the osteotome should be directed cephalad and away from the sciatic notch.

In the posterior superior iliac spine, if graft is harvested too far posteriorly, the sacroiliac joint can be inadvertently

breached or the posterior sacroiliac ligaments may be compromised, leading to sacroiliac joint instability, pain, and arthrosis. A positive Trendelenburg gait with stance phase pain may occur with over-stripping of the hip abductor attachments to the ilium.

Minimally Invasive Surgery

Despite the advantages of reducing muscle retraction, blood loss and postoperative pain, the limited visualization associated with minimally invasive surgery may lead to unique complications. Radicular injury from manipulation in a tight cervical neural foramen or direct mechanical spinal cord injury during dilation or decompression can occur. Inadvertent nerve injury can occur during insertion of the blunt dilator and it should be inserted with fluoroscopic imaging to prevent it from entering the interlaminar space. Dural tears are more common and has been reported to occur in 1.6-6.6% of procedures.¹⁴⁻¹⁷ The dura could be injured during drilling and complications such as epidural hematoma, progressive quadriplegia, C5 nerve palsy could occur. With dural injury, repair is more difficult with limited access and exposure provided by the small tubular retractor.

For minimally invasive anterior odontoid screw fixation, postoperative hematoma, dysphagia, hoarseness, vascular or neural injuries can occur. Transoral approaches can lead to infections, pharyngeal wound breakdown, meningitis, vertebral artery injuries and cerebrospinal fistulas. Schaefer et al. showed that 23.6% of screws caused pedicle wall perforation, most causing lateral wall perforation (76.4%).¹⁸ The incidence is highest in C3 and C5 followed by C4, and 7 of 72 screws (9.7%) caused narrowing of the transverse foramen of >25%.¹⁸ One must always be cognizant of the potential risk to the esophagus when using drills and other instruments through an anterior cervical approach.

Wound Infection and Discitis

The incidence of postoperative wound infections in anterior cervical discectomy and fusion is very low and is estimated to be between 0.1% and 1.6%.¹⁹ Postoperative infection usually presents as pain. Fever, chills and night sweats can also occur in more advanced presentations. Local wound changes such as erythema or drainage can also occur. In anterior cervical procedures, patients may present with painful swallowing due to a retropharyngeal collection. Epidural abscesses may cause neurological

complications without treatment. Infectious organisms can also tract into the disc space. Long-term prognosis of discitis is generally good at 90% of patients being pain-free and 75% of patients developing spontaneous bony fusion or stable fibrous union within 2 years of diagnosis of infection.²⁰

Surgical time correlates with the bacterial numbers found in the wound. More than 10⁵ organisms can be found in surgical wounds after 5.7 hours,²¹ and operative times >3 hours increase risk of infection.²² Meticulous soft tissue dissection, staying in avascular planes, avoiding the creation of large flaps and potential dead spaces, frequent release of retractors, careful hemostasis and frequent irrigation can help reduce infection.

Culprits in acute infection are usually gram-positive cocci including *Staphylococcus aureus*, *Staphylococcus epidermidis* and β -hemolytic streptococci.²²⁻²⁴ *Klebsiella*, *Escherichia coli*, *Pseudomonas*, *Aerobacter* and *Proteus* are possible gram-negative species commonly present in intravenous drug users. Delayed or chronic infections are usually caused by skin flora of low virulence such as *Propionibacterium*²⁵ and *Diphtheroids*.²⁴

ACCESS RELATED

Surgical Exposure in Anterior Surgery: Dysphagia, Dysphonia and Neck Soft Tissues

Recurrent Laryngeal, Superior Laryngeal and Hypoglossal Nerve Injuries

Reported rates of vocal cord paralysis range from 0.07% to 11%, and the incidence of permanent paralysis ranges from 0.15% to 3.5%.²⁶⁻²⁸ Most vocal cord paralysis is transient lasting for weeks to months. Causes of injury include direct surgical trauma, nerve division or ligature, pressure, stretch-induced neuropraxia, and postoperative edema. Of these, prolonged pressure on the nerve is the most likely cause that decreases mucosal and neuronal capillary blood flow and increases risk of nerve injury.

Careful dissection with proper retractor placement under the bodies of the longus colli muscles and away from the tracheoesophageal groove can prevent injury to the recurrent laryngeal nerve. Longus colli muscles should be elevated cleanly without shredding them to maintain a firm anchor point for retractors. Sharp-toothed retractor blades are advised as they have better anchorage. Blunt tooth blades easily slide anteriorly to compress the trachea

or esophagus medially and the carotid artery laterally. Intermittent release of retraction can also prevent injury. The pressure exerted by the retractor is also important.

The endotracheal tube accounts for 11.2% of recurrent laryngeal nerve paralysis.²⁹ The shaft of the tube can impinge on the lateral wall of larynx, compressing the endolaryngeal portion of the recurrent laryngeal nerve, as it transverses submucosally to enter the vocal cord musculature. Releasing the cuff pressure to deflate the balloon can allow the tube to shift away from the inner laryngeal wall. The cuff can be reinflated to just-sealed pressures. Laryngeal displacement against the endotracheal tube after retractor placement should also be avoided.

Patients may complain of difficulties in singing high notes with superior laryngeal nerve injury. This nerve (C3-C4) can be damaged via an anterior approach to the cervical spine. Hypoglossal nerve injury during dissection of the anterior triangle of the neck at C2-C4 occurs up to 8.6%.³⁰ The nerve is especially at risk in high retropharyngeal approaches to the upper cervical spine where the nerve may traverse the field and may appear to resemble a large blood vessel. Postoperative diagnosis is also difficult as palsy causes dysphagia and dysarthria, symptoms associated with esophageal or recurrent laryngeal nerve injury.

Esophageal Injury

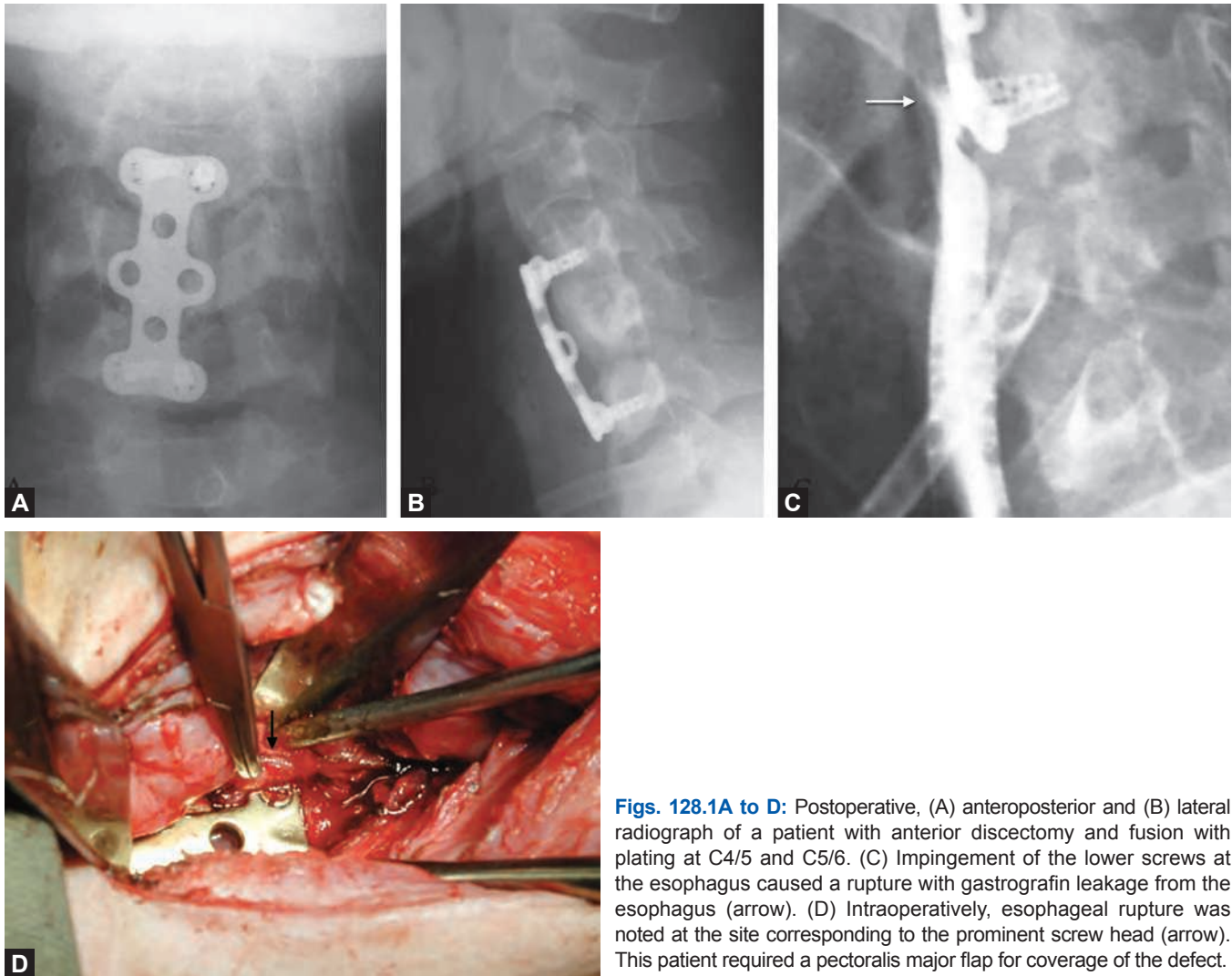
Iatrogenic dysphagia is usually transient with quoted postoperative incidence of 9.5%.¹⁹ Intraoperative retraction of the esophagus is the most common cause of postoperative dysphagia due to ischemia of the pharyngeal/esophageal wall due to retractor blades, leading to reperfusion trauma with edema and swelling. Thus, intermittent release of the retractors can avoid injury to the esophagus. Other causes of dysphagia include postoperative swelling, hematoma, infection, neurological injury to pharyngeal plexus, superior laryngeal nerve or recurrent laryngeal nerve, scar formation around cervical plates and bone graft dislodgement. In prolonged cases, videofluoroscopic swallowing study can be used to determine swallowing integrity. Reduced pharyngeal wall movement, impaired upper esophageal sphincter opening, incomplete epiglottic deflection and postswallow residue in the vallecula, pyriform sinuses and posterior pharyngeal wall can be observed on swallowing studies or with direct video endoscopy.³¹

Esophageal perforation (Figs. 128.1A to D) has an incidence of 0.2–1.15%.^{28,32,33} To avoid the complication, blunt finger dissection below the superficial cervical fascia can

reduce the risk. Proper retractor placement can mobilize the esophagus away from the operative field to prevent injury. The region of the esophagus that is most at risk of perforation with instrumentation is the cricopharyngeal region of the cervical esophagus, where the posterior esophageal mucosa is covered only by a thin fascial layer.³⁴ Delayed perforations after surgery are mostly related to direct erosion of the esophagus by bone, cement, hardware and screw backout or migration.³⁵ Methylene blue is a good tool that can check for the site of perforation. It should be injected into the oral-pharyngeal tube to identify any perforations. Complications arising from esophageal perforations such as wound breakdown, malnutrition, mediastinitis, esophageal stricture, osteomyelitis, pneumonia, prevertebral or retropharyngeal abscess and tracheoesophageal fistulas can result in high morbidity.³³ Mortality is as high as 15–30% and may be >50% if treatment is delayed.^{32,33} Neck pain and crepitus should raise alarms for esophageal perforation and secondary infection. Other symptoms include dysphagia, hoarseness, aspiration, fever, leukocytosis and tachycardia. Lateral plain films of the neck can show subcutaneous emphysema, widening of retropharyngeal or retroesophageal space due to edema or fluid collection, presence of prevertebral air, and migration of the internal-fixation materials. Contrast pharyngoesophagography, flexible fiberoptic endoscopy and computed tomography are other useful diagnostic tools to detect location of perforation and extension of extravasation. Endoscopy can show the site of perforation and computed tomography scans detect abscess and any graft displacement. Common organisms involved in infections postesophageal perforation are *Streptococcus*, *S. aureus*, *Pseudomonas*, *Bacteroides*, anaerobic gram-positive cocci and *Candida albicans*.³³

Vertebral and Carotid Artery Injuries

Injury to the vertebral artery ranges from 0.3% to 0.5%.^{36,37} The uncinate process is an important bony landmark that signifies the lateral border of the spinal canal, and the medial uncovertebral joint should be used as the lateral extent for dissection or drilling. Ventral decompression can usually be carried out to a width of 18–20 mm. Extensive lateral procedures such as decompression of uncovertebral joints or neural foramen, lateral disc removal, posterolateral corpectomy, lateral placement of instruments can all cause injury to the vertebral artery. The artery is most susceptible during surgery anterior to transverse foramen of C7 or during lateral decompressive maneuvers



Figs. 128.1A to D: Postoperative, (A) anteroposterior and (B) lateral radiograph of a patient with anterior discectomy and fusion with plating at C4/5 and C5/6. (C) Impingement of the lower screws at the esophagus caused a rupture with gastrografin leakage from the esophagus (arrow). (D) Intraoperatively, esophageal rupture was noted at the site corresponding to the prominent screw head (arrow). This patient required a pectoralis major flap for coverage of the defect.

from C3 to C6. The longus colli muscles and uncovertebral joints are structures labeling for a secure midline dissection during cervical discectomy or corpectomy.

Some patients may remain asymptomatic due to adequate collateral circulation but others will have devastating vertebrobasilar ischemia or fatal bleeding and vascular embolic complications. Injury to carotid artery is a result of improper and excessive retraction or inadvertent laceration with scalpel or other instruments. Prolonged pressure against the carotid artery can cause thrombosis or cerebral ischemia. Manipulation can also dislodge plaques, causing intracranial embolus. Pollard et al. showed by duplex ultrasound that 14% decrease in cross-sectional area occurs with placement of retractors that reaches 30% at the end of surgery.³⁸

Tracheal Injury

Tracheal injury is life-threatening and can result in tension pneumothorax, mediastinal emphysema and esophageal prolapse into the tracheal lumen leading to acute asphyxia, sepsis and mediastinitis.³⁹ There is also a chance of tracheal stenosis formation.

Thoracic Duct Injury

Thoracic duct injury can occur during left-sided neck dissection. The thoracic duct can be identified, as it enters the dorsal aspect of the subclavian vein and should be protected. Injury results in chylorrhea and postoperative skin flap erythema and edema may be the first indication of a chylous fistula.⁴⁰ Chronic loss of chyle can cause metabolic derangements secondary to depletion of fluid,

electrolytes and protein, and also decreased immune status by peripheral lymphocytopenia. Patients may have progressive weakness, dehydration, and peripheral edema.

Sympathetic Chain Injury

Cervical sympathetic chain injury is rare (4.2%).²⁷ Injury causes ipsilateral Horner's syndrome. The cervical sympathetic chain is located between the carotid sheath and longus colli muscles in the midcervical region. Excessive lateral retraction or extensive dissection of the longus colli muscles from midline can cause injury.

Pharyngocutaneous Fistula

Pharyngocutaneous fistulas are rare complications of anterior spine surgery with occurrence of <0.1%.⁴¹ Perforations may occur as direct trauma to the esophagus during dissection, decompression of the spine with a high speed burr or fixation of the anterior cervical spine.

Revision Surgery

In revision surgery with the scar formation, greater diligence is required during dissection. Up to 10.5% of patients have transient recurrent laryngeal nerve palsy in the literature.⁴² Esophageal injury may carry a higher risk in revision surgery due to the difficult dissection, previously established esophageal dysmotility and scar tissue.⁴³ In revision anterior cervical surgery, it is recommended that the exposure be performed on the same side as the prior surgery. Patients may have a subclinical recurrent laryngeal nerve injury from their index surgery and if a contralateral approach is performed, then there is the risk of bilateral nerve injury, an extremely morbid complication.

Posterior Surgery

Ossified Posterior Longitudinal Ligament

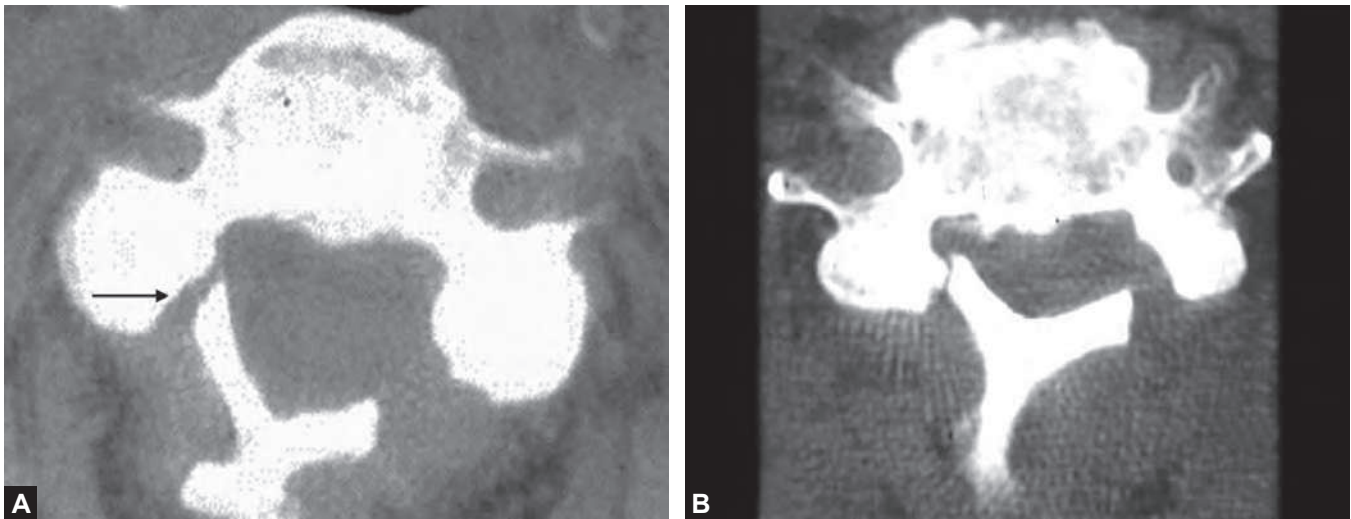
In surgery for ossified posterior longitudinal ligament (OPLL), the reported postoperative incidence was 2–10% for quadriplegia and was 5–17% for root injury (usually involving C5).⁴⁴ An anterior approach is required to directly remove the ossified ligament but has a high risk of dural tear, bleeding from epidural venous plexus and spinal cord injury. Dural tears can be avoided if the anterior ossified lesion is left alone, since it is usually adherent to the dura mater. Anterior decompression for OPLL requires a more

lateral decompression as the OPLL expands laterally at the intervertebral disc level. This also carries risk of injuring the vertebral artery if exploration is lateral to the uncinate process.

Cervical Myelopathy

Woods et al. showed that laminectomy carries with it a greater loss of cervical lordosis and higher tendency to develop junctional kyphosis as compared to laminoplasty when applied for the treatment of cervical myelopathy.⁴⁵ Diminution of range of motion of the neck and increased neck pain are noted in almost all series with a mean loss of 50% of cervical range of motion in Hirabayashi-type laminoplasty.^{46–48} Yonenobu et al. studied 384 patients with cervical myelopathy and found 3.4% incidence of early postoperative C5 nerve root deterioration and 2% incidence of early postoperative spinal cord dysfunction.⁴⁴ Segmental (C5) root level motor palsy is relatively common after cervical laminoplasty with an incidence of 5.5–12% and results in deltoid and biceps weakness.^{49,50} Palsies are motor-dominant but sensory and radicular pain are also possible. C5 dysfunction can occur immediately to 20 days after operation.⁵⁰ Recovery usually occurs over weeks to months but has been reported to take as long as 6 years.⁵¹ The cause is likely due to nerve root traction as the decompressed cord floats posteriorly. The C5 root has a direct, short course with little redundancy, as it exits the spinal cord. As the spinal cord drifts posteriorly after laminoplasty, tethering of the C5 root may occur and stretched beyond its limits of tolerance. C5 is also at the apex of lordosis, so the postoperative spinal cord shift and root traction is greatest at that level. The deltoid is innervated by a single root and C5 nerve root dysfunction has a profound effect on function. Prophylactic C5 foraminotomy may be required in these cases.

Spring-back closure after laminoplasty (Figs. 128.2A and B) has a reported rate of 40% by Mochida et al.⁵² Lee et al. found that at 6 months postoperatively, the AP diameter increase after surgery and opening angle (angle between line connecting medial end of bilateral facet joint and the line connecting the bilateral end of the opened lamina) was reduced by approximately 10% after open-door laminoplasty was performed.⁵³ For double-door laminoplasty, postoperative migration of the cervical spinal cord between the split laminae has been known to cause worsening myelopathy. Plating has not been proven to hold open the hinge in open-door laminoplasty.



Figs. 128.2A and B: Axial computed tomography scans showing (A) hinge fracture (arrow) after laminoplasty and (B) spring back closure.

■ DECOMPRESSION RELATED

Injury to Spinal Cord and Nerve Roots

Injury to the spinal cord can occur during patient positioning, decompression, fusion, fixation or closure. The overall incidence of neurological complications have been reported as 0.18%⁵⁴ and increases with correction of severe cervical kyphosis (2.6%).⁵⁵ The most common etiology is epidural hematoma (0.07%), inadequate decompression (0.04%), vascular compromise (0.03%), graft/cage dislodgement (0.02%) and surgical trauma (0.02%).⁵⁴ Posterior surgery is usually riskier due to sublaminar, interspinous wiring and hooks, lateral mass screws, and pedicle screws. Direct injury to the spinal cord in anterior decompression is rare but may occur in the presence of significant stenosis. Injury is usually caused during osteophyte removal with Kerrison rongeurs or by a drill. Often this complication is not detected until postoperatively. Meticulous hemostasis, adequate illumination and visualization, experience and proper technique are important to avoid this complication. Injury to the spinal cord could also be caused by tapping the bone graft into place after discectomy. Proper appropriate size and shaping of the bone graft and tapping it in place with proper depth and height can avoid bone graft extrusion. Adequate hemostasis can prevent epidural hematoma.

Late postoperative neurological complications can be avoided in posterior reconstruction surgery for cervical

kyphosis correction by prophylactic foraminotomies in the presence of foraminal stenosis, avoiding excessive correction of cervical kyphosis exceeding 9.7° per segment, and avoiding kyphosis correction at C4/5 which causes a most dramatic posterior shift of the spinal cord at the C4/5 segment leading to C5 palsy.^{55,56}

Dural Tear, Cerebrospinal Fluid (CSF) Fistula, and Pseudomeningocele

The risk of durotomy during laminectomy is quoted as 0.3–13% and up to 18% with revision surgery.^{57,58} Risk factors can include old age, thin dura due to chronic compression, ossification of the ligamentum flavum, synovial cysts, scar from prior surgery and surgeon inexperience. Incidental durotomy can present as postural headache, nausea, vomiting, dizziness, photophobia, tinnitus and vertigo but are typically asymptomatic. Symptoms are caused by intracranial hypotension leading to traction on the supporting structures of the brain. CSF leaks can result in inadvertent intraoperative durotomy and may lead to meningitis and brain abscess. The ligamentum flavum and posterior longitudinal ligaments are helpful barriers during decompression of the dura and these soft tissues should be carefully elevated. Persistent CSF leakage is associated with formation of CSF fistulas or pseudomeningoceles. Reported rates of dural tears and cerebrospinal fistula formation after anterior cervical corpectomy vary from 0% to 8.3% and may be as high as 32% in the presence of OPLL.⁵⁹⁻⁶²

■ INSTRUMENTATION/IMPLANT RELATED

Cervical Traction

Local complications of cervical traction include calvarial pin penetration into the dura, pin tract infection, brain abscess, meningitis, propagation of skull fracture, loss of pin fixation, hanging weight complications, arterial injury, missed distraction injury, overdistractive, traction-related disc protrusion, misapplication of pins leading to canal compromise and fracture malalignment. Systemic complications are due to prolonged bed rest include pneumonia, global neurological compromise, thromboembolism, sepsis and decubitus ulcers.

Intracranial pin penetration is rare and is usually associated with falls, overtightening of pins, prolonged halo use, poor patient compliance and improper pin placement. Garfin et al. reviewed 179 patients with halo insertion and reported pin loosening in 36%, pin-site infection in 20%, pin discomfort in 18%, cosmetically disfiguring scars in 9%, nerve injuries in 2% and dural penetration in 1% of patients.⁶³ Pediatric patients have more complications up to 68% with most being pin-site infections.⁶⁴ Due to the relatively thin skull in children, many authors have recommended multiple pins (6–8 pins), special pin designs,⁶⁵ well-calibrated torque wrenches⁶⁶ and lower insertion torques (4–6 in-lb) to prevent skull penetration.⁶⁷

Loss of fracture reduction or spinal alignment may be caused by pin loosening. Failure usually occurs at the pin-bone interface and may lead to neurological compromise. Thus, regular recalibration and replacement is necessary. Loosening of pins is also common with infection and these pins should not be retightened with risk of inner skull penetration. Penetration and pin site infection can lead to brain abscess or meningitis, which is associated with a mortality rate of 24%.⁶⁸ Injury to the temporal artery can also occur from traction pins due to direct laceration or pin site invasion. Ideally, the pins should be placed at the thickest part of the skull bone just above the external auditory meatus. The area directly anterior and superior to ear tragus should be avoided.

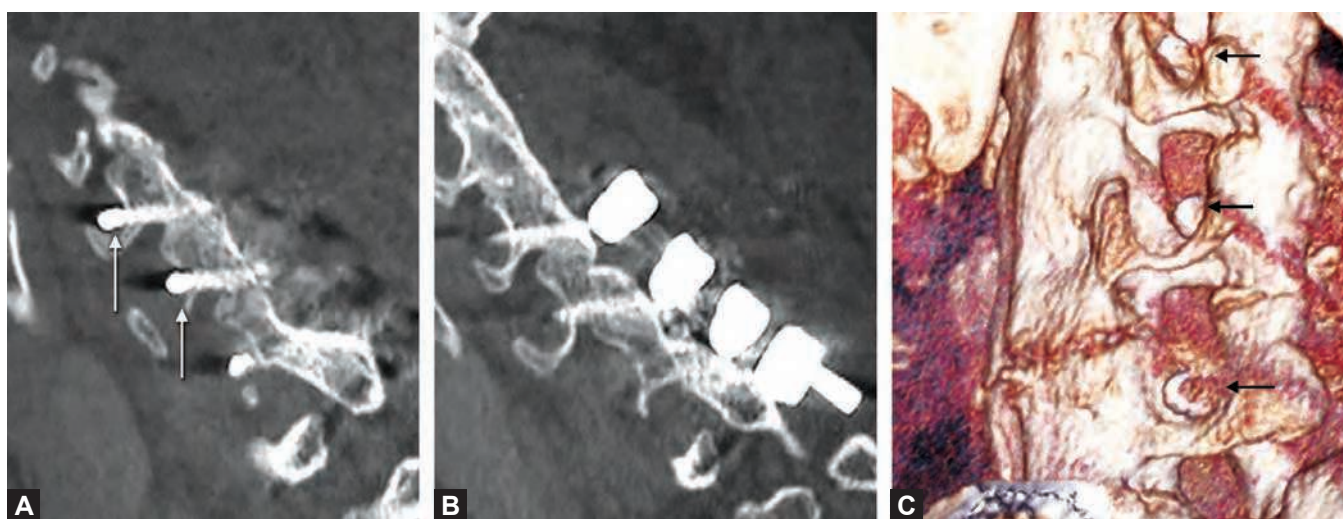
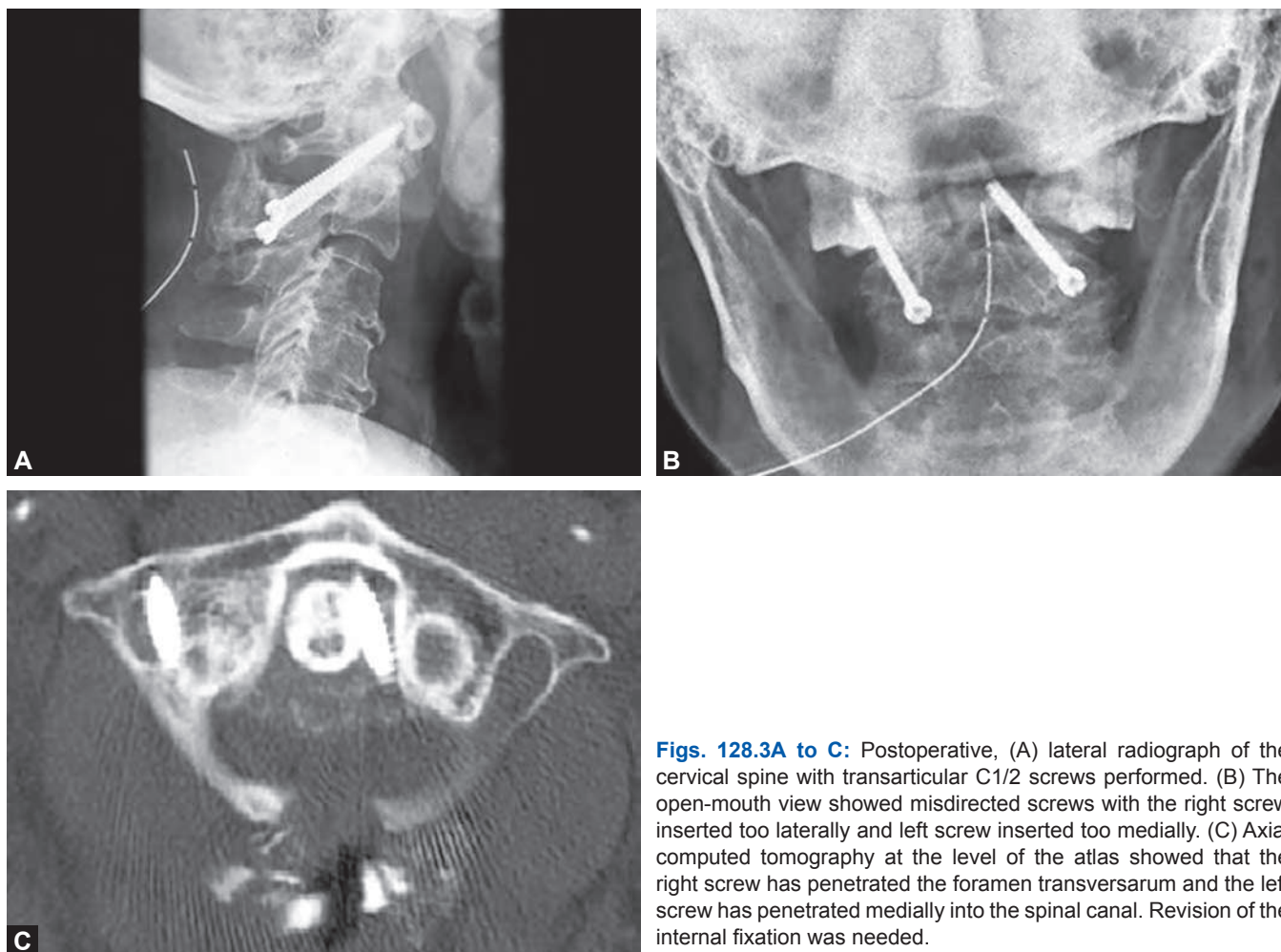
In cases of occipitocervical dislocations, odontoid fractures, ankylosed spine, hyperextension and distraction injuries, overdistractive must be avoided. Overdistractive may cause cranial nerve injuries (abducens, glossopharyngeal, vagus, hypoglossal) with an incidence of 0.07%.⁶⁹ Causes

include neuropraxia injury, ischemia due to edema, direct bony compression or stretching or kinking of the nerve. In patients with ligamentous laxity, other complications include focal cervical kyphosis (16%), loss of normal cervical lordosis (35%) and atlantoaxial subluxation >3 mm (20%).⁷⁰ This is explained by overdistractive and tensioning of the musculoligamentous element stretching beyond its elastic limit.

Screw Fixation

Anterior fixation has higher rates of technical complications (17%) such as loosening of screws or implant, implant cutout, secondary loss of reduction, incorrect reduction, malpositioning of implants, or abandoning the technique intraoperatively as well as need for revision surgery than does surgery performed with posterior fixation (8%).⁷¹ Screw malposition varies from 0% to 4% in the atlas and 0% to 7% in the axis.^{72–74} Transarticular C1/2 screws or Magerl screws in addition have complications of vertebral artery injury, neurological deficit or inadequate bony purchase (Figs. 128.3A to C). Vertebral artery injury is one of the most dangerous complications of screw fixation and is usually due to incorrect cervical pedicle screw entry points with vertebral artery injury. Iatrogenic vertebral artery injury has an incidence of 1.3–4% for Magerl fixation⁷⁵ but fortunately the risk of neurological deficit after injury is only 0.2%.⁷⁶ Mortality, however, is greatly increased if both vertebral arteries are injured. Neo et al.⁷⁷ showed that 84% of screws showed lateral deviation that can lead to violation of the transverse foramen and vertebral artery injury. Current trends include the use of computer-assisted navigation systems that can improve screw trajectory. Ludwig et al.⁷⁸ reduced their perforation rate to 24% and Richter et al.⁷⁹ reported only 3% of screws perforated the pedicles. Medial perforation due to screw insertion seldom cause injuries to the spinal cord because of the wide space between the cord and medial wall of the pedicle.

Subaxial lateral mass screws have a risk of nerve root injury (1.3%) and lateral mass fracture.⁸⁰ Direct root injury during lateral mass screw insertion can be avoided with fluoroscopic control. Screws with a sagittal angulation of <15° are associated with a risk of screw thread impingement on the exiting nerve root (Figs. 128.4A to C).⁸⁰ Screw holes with axial trajectories >30° lateral to midline usually cause no neurological harm but have a risk of lateral mass fracture (1.6%) or screw cutout (1.3%).⁸⁰ Screws placed too medially can cause injury to the vertebral artery.



Corpectomy

The overall morbidity risk associated with corpectomy is quoted as 11–27%, most commonly caused by postoperative dysphagia, hematoma and recurrent laryngeal nerve palsy.^{81–84} Despite the high rate of complications, the mortality rate has been reported to be only 0.1%.¹⁹ Corpectomy has a higher risk of graft-related complications than discectomy including graft migration, strut graft dislodgement, infection and pseudarthrosis.⁸⁵ Other complications include graft pistoning, mortise penetration, failure of the internal fixation device with undesirable deformity or irritation or injury to surrounding vital or neurological structures. Late causes of failure include graft fracture, collapse or subsidence.

Most graft dislodgement occurs within 24 hours postoperatively. Wang et al. studied 249 patients over a 25-year period and found that graft migration rates increased with more levels of fusion (odds ratio of 1.65 for having a displaced graft with each additional level).⁸⁶ Most dislodgements occurred at the C6 level and extension to C7 level (14 of 16 patients) and 5 of these patients required revision surgery.⁸⁶ The likely cause was the junction between cervical lordosis and kyphotic angulation of the sagittal inclination at the cervicothoracic junction, causing increased stress at the graft endplate interface and higher probability of graft extrusion. If the posterior elements are deficient such as postlaminectomy, compression and shear loads through the strut graft are greater increasing the likelihood of failure with graft fracture, subsidence and dislodgement. Supplemental external immobilization with halo vest can be given to theoretically increase the rigidity of the construct and decrease the chance of cage dislodgement especially in long fusions. Partial dislodgement may be closely observed but total dislodgement require another operation, as there is risk of esophageal irritation or penetration with subsequent mediastinal infection. Graft collapse commonly occurs with osteopenic bone. Subsidence and mortise penetration occurs with loss of graft height or penetration into the endplate at the graft-vertebral junction. This may result in kyphosis or loss of structural integrity, leading to sagittal imbalance and muscle spasms. Neurological compromise can even occur with the spinal cord pulled against the apex of the kyphotic deformity. To combat these graft migrations, an additional cervical buttress plate may be indicated.

Anterior plating decreases local motion at the corpectomy site and improves the stability of the construct. However, the center of rotation will be shifted to anterior surface of the spine where the plate is located. Any

subsidence of the strut graft will transfer all compressive loads to the plate leading to failure. The site of failure occurs most commonly at the lower graft junction often with plate and strut graft dislodgement. Dynamic plates theoretically allow continued contact between the graft and the endplate after graft subsidence and improve the chance of obtaining fusion by compressive load on the graft. However, results are controversial with reports of higher nonunion rates with dynamic plates (16%) versus static plates (5%) due to failure of angular motion between screws and plates.⁸⁷

Posterior Occipitocervical Instrumentation

In occipitocervical instrumentation, precise insertion of the occipital screws is crucial to prevent complications. Any screws inserted cephalad to the superior nuchal line can injure the transverse sinus. Loosening of screws is noted in 4.2–7% of cases and rates of dural tears during drilling of the occiput and screw placement range from 0% to 4.2%.^{88,89} For wire-based fixation, dural laceration can occur during drilling of the occipital burr holes or recoil of the wiring with reported rates of 25–28%.^{89,90} Dural laceration leads to CSF leak but screw placement usually is sufficient to halt a CSF leak. Late complications of occipitocervical fusion can include pseudarthrosis (6%) and adjacent level degeneration (7%).⁹¹

Cervical Disc Arthroplasty

General complications are similar between fusion and disc replacement. Although there is a higher rate of adjacent disc degeneration in the fusion group, there is no difference between the two groups in terms of revision rate up to 2 years of follow-up.⁹² There are only two studies that demonstrate a marginal but clinically questionable benefit of disc replacement over fusion for the endpoint “overall success.”^{93,94} However, “overall success” was not adequately defined. Huppert et al. found at 2 years of follow-up that 2.3% of patients required revision surgery in single level arthroplasty and 3.6% of patients required revision surgery in multilevel arthroplasty.⁹⁵

FUSION RELATED

Adjacent Segment Degeneration

Up to 15% of anterior cervical discectomy and fusion^{96–98} and 9% of all posterior surgery develop adjacent segment disease.⁹⁹ Hilibrand et al. performed a study with follow-up of 21 years and found that in 409 procedures for 374

patients, there was a prevalence of 13.6% of symptomatic adjacent segment disease at 5 years and 25.6% at 10 years.⁹⁶ The risk of developing adjacent segment disease was 3% per patients per year.⁹⁶ Fusionless surgery is theoretically thought to be unlikely to develop adjacent segment disease, although this is debatable.

Pseudarthrosis

The incidence of pseudarthrosis in cervical spine surgery has been reported as 0–50%.^{100–105} Risks of pseudarthrosis include nicotine produces, osteoporosis, number of levels fused, surgical technique, use of antimetabolic agents such as phenytoin, nonsteroidal anti-inflammatory agents (some avoid for at least 10 weeks as they reduce osteoblastic activity), collagen disorders and location of fusion. For patients undergoing anterior cervical discectomy and fusion, pseudarthrosis developed in 33.3% of smokers while in nonsmokers, the rate was 9.6%.¹⁰⁶ Fusion along the posterior para-axial spine and related to degenerative disc disease has higher rate of pseudarthrosis compared to the anterior axial spine.¹⁰⁷

Nonunion rates in odontoid fractures range from 35% to 85%.¹⁰⁸ There is higher risk in elderly with 75% of fibrous nonunion cases found in patients over age of 65.¹⁰⁹ Other factors influencing nonunion especially in Type II odontoid fractures treated with halo immobilization include extent of neurological damage, degree of dens displacement, presence of concomitant C1–C2 fracture, pathological fracture and age of fracture. Radiograph features of pseudarthrosis include extrusion of instrumentation, lucencies across interbody endplate or interbody fusion cage endplate, lucencies around posterior lateral mass screws, instrumentation failure such as broken screws or rods, or gross movement across the fused segment suggests pseudarthrosis. Change of 2 mm in distance between tips of posterior spinous process on flexion and extension lateral radiographs is also suggestive of pseudarthrosis.¹¹⁰

Bone substitutes such as bone morphogenetic proteins (BMP) are commonly used to improve fusion rates. However, there are multiple recent reports of serious complications associated with BMP use including heterotopic ossification forming outside the disc space and into the spinal canal or neuroforamen in 20.8–75% of patients.^{111,112} Vertebral osteolysis has also been described in up to 82% of cases.^{113,114} Other complications include massive airway edema, discharging wound seroma, hematoma formation



Fig. 128.5: Lateral radiograph showing a postlaminectomy kyphosis after C2–C4 laminectomy.

and radiculopathy caused by increased inflammation with use of BMP. Routine use of BMP in the cervical spine is not recommended.

■ DELAYED OR LATE COMPLICATIONS: POSTLAMINECTOMY KYPHOSIS

The incidence of postoperative kyphosis after multilevel cervical spine laminectomy (Fig. 128.5) is 20%.¹¹⁵ Older patients may have partially fused cervical spines and are more stable, thus postoperative kyphosis is more common in younger patients. Laminectomy leads to loss of spinous processes, inter and supraspinous ligaments, laminae and ligamentum flavum, and loss of capsules of facet joints that compromise the posterior stabilizers. With continuing normal flexion forces, kyphosis will result. Kyphosis develops gradually which is why patients are usually well in the early postoperative period. Constant contraction of neck extensor muscles will occur, causing muscle fatigue and neck pain. Progressive kyphosis in children leads to wedging of anterior vertebral bodies due to compression of growing cartilaginous endplates. Sagittal malalignment and axial neck pain are the main issues regarding postlaminectomy kyphosis while neurological deficit is rarely encountered. Laminectomy should be avoided for young patients with lack of preoperative lordosis and disruption of posterior facet joints should be avoided intraoperatively. Fusion should be considered for these patients at the same procedure.

KEY POINTS

- Avoiding prolonged and forceful retractions in anterior surgery can prevent injury to the esophagus, recurrent laryngeal nerve and carotid arteries.
- Prophylactic C5 foraminotomy may help reduce the risk of postlaminoplasty C5 nerve root palsy.
- Careful analysis of the bony and vascular anatomy should be done preoperatively especially when internal fixation is contemplated.
- Additional anterior plating in corpectomy may improve the stability of the construct but failure may occur with graft subsidence.
- Preservation of posterior muscles and their attachments are important for prevention of postoperative neck pain and delayed kyphosis.

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This is a study of patients with graft migration after corpectomy over a 25-year follow-up. This study demonstrated the risk of graft migration with increased levels of corpectomy and which cases required revision surgery.
- Hilibrand AS, Carlson GD, Palumbo MA, et al. Radiculopathy and myelopathy at segments adjacent to the site of a previous anterior cervical arthrodesis. *J Bone Joint Surg Am.* 1999;81(4):519-28.
This was one of the earliest and larger series that identified the problem of symptomatic adjacent-segment disease after anterior fusion of the cervical spine.

Complications of Anterior and Posterior Thoracic Spine Surgery

Atsushi Seichi

Snapshot

» Complications of Anterior Surgery for the Thoracic Spine

» Complications of Posterior Surgery for the Thoracic Spine

INTRODUCTION

Surgery-related complications during thoracic spine surgery, particularly anterior thoracic surgery, carry with them potentially dire outcomes, including death. Evidence-based descriptions on how to prevent complications during thoracic spine surgery are actually difficult to provide. Spine surgeons dealing with thoracic spine surgery should be familiar with the management of intra- and extraspinal canal adverse events, through practice and learning from senior doctors, journals, and textbooks. In the author's country (Japan), decompression surgery for extensive thoracic ossification of the posterior longitudinal ligament (OPLL) or thoracic spinal tumor is representative of a majorly challenging spine surgery (Fig. 129.1). Both posterior and anterior surgeries for thoracic OPLL carry a potential risk of spinal cord injury with or without direct trauma to the spinal cord from the high speed burr, and surgery-related complications are common in the treatment of thoracic OPLL.^{1,2} Information on surgery-related complications in patients with thoracic OPLL can be generalized to any kinds of thoracic spine surgery. This chapter therefore focuses mainly on complications of thoracic OPLL surgery.

COMPLICATIONS OF ANTERIOR SURGERY FOR THE THORACIC SPINE

Wrong Level Surgery

Wrong level surgery is an unavoidable technical error rather than a true complication. In extremely obese



Fig. 129.1: Computed tomography of thoracic ossification of the posterior longitudinal ligament.

patients, confirmation of spinal level from intraoperative radiography using a portable X-ray apparatus is not a completely reliable method for the surgeon to accurately pinpoint the correct level of the anterior thoracic spine. It is not recommended to simply rely on a lateral intraoperative radiograph in the thoracic spine. Reconfirmation using an image-intensifier, with anteroposterior

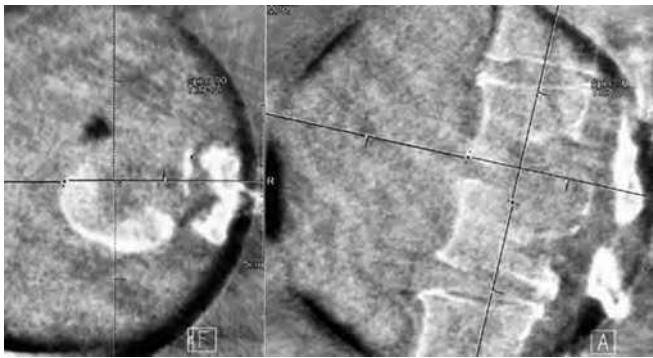


Fig. 129.2: Snapshot of intraoperative computed tomography after anterior decompression surgery.

views in the operating room, is thus recommended. After finishing decompression procedures, confirmation of the level and evaluation of decompression status by intraoperative CT scan is also helpful (Fig. 129.2).

Vascular Complications

Vascular complications during anterior thoracic surgery are probably under-reported and the true prevalence is unclear. Anterior thoracic surgery carries a potential risk of major complications even in surgery by experienced spine surgeons.³ Direct vascular injuries due to technical errors should be avoided, given the inherent risk of death. Spine surgeons should be very familiar with the vascular anatomy during anterior thoracic approaches, including transthoracic, and sternum-splitting approaches (Fig. 129.3). Care should be taken to prevent contact between vessels and edges of surgical tools, including electrical coagulators. Although experienced spine surgeons seldom encounter an operative shambles, they must have skills to deal with any kind of vascular complication and be able to work closely with reliable chest surgeons and cardiovascular surgeons who can help them.

If a surgeon injures a segmental artery during an anterior approach, the bleeding must be stopped by ligation or coagulation after compressing the bleeding site using a peanut dissector. In patients with chronic vertebral infection, identification and dividing of the segmental vessels is not easy during exposure of the lateral and anterior aspects of the thoracic vertebral bodies.

The aorta is more elastic and less susceptible to injury from retraction than veins. However, intraoperative penetration of a screw placed into a vertebral body can occur and risks creation of a spurious aneurysm and/or fatal

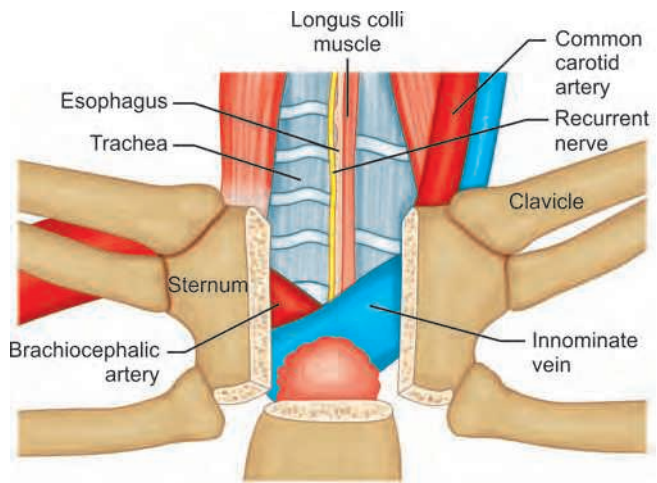


Fig. 129.3: The sternum-splitting approach. Knowledge of the location of the innominate vein (brachiocephalic vein) in the upper chest is critical to avoid injury to this vessel during the sternum-splitting approach.

pulmonary embolism.⁴ When a screw is inserted from the right side of the vertebral body, an overly long screw can penetrate into the aorta on the left side. Precise measurement of the diameter of the vertebral body in which the screw is to be inserted is thus crucial.

The walls of major veins are thin and easily damaged. If an injury to the inferior vena cava or azygos vein occurs, a surgeon has to press strongly on or caudal to the bleeding site with a finger or peanut dissector until a reliable cardiovascular surgeon can assist. The spine surgeon alone trying to effect repairs is likely to only make the situation worse. With a sternum-splitting approach, mobilization, or retraction of the innominate (brachiocephalic) vein without sufficient release of this large vein from the surrounding tissue can lead to its injury. With such injury, the surgeon has to quickly capture the injured site using vessel forceps and make repairs by suturing.

Control of epidural bleeding during anterior thoracic decompression surgery is difficult. To prevent such troublesome bleeding in anterior surgery for thoracic OPLL, the anterior floating technique of thoracic OPLL after thinning the ossified mass using a high-speed diamond burr under microscopy is recommended (Fig. 129.4). Removal of ossified mass may cause excessive bleeding or cerebral spinal fluid (CNS) leakage at the lateral margins of the ossified mass, and this is applicable to anterior surgery for any kind of anterior lesion, including large thoracic disc herniation with calcification. Control of epidural bleeding from a congested Batson's venous plexus

is extremely difficult in patients in the lateral decubitus position, and bipolar coagulation for this bleeding is almost always ineffective. Surgeons must have the skill to manage epidural bleeding by application of hemostatic agents and covering of the agents with surgical sheet (Fig. 129.4).

Spinal Cord Injury

The author prefers microscopic decompression for anterior thoracic spine surgery to prevent spinal cord injury

caused by the high-speed burr. Spinal cord injury may also result from inadequate release of the OPLL (Fig. 129.5A and B). To avoid incomplete decompression due to disorientation to the spinal canal, the author developed anterior navigation surgery for thoracic OPLL.⁵ However, such tools are not available everywhere. Confirmation of complete decompression by intraoperative CT is helpful (see Fig. 129.2).

Injury to the Lung and Pulmonary Complications

Although a chest tube assists lung re-expansion, anterior access to the upper thoracic spine sometimes causes lung atelectasis and pneumonia. Serial chest radiography should be performed after anterior thoracic surgery. Management by a chest surgeon using a bronchoscope is necessary for atelectasis. Tight closure of the chest wall is mandatory to prevent pneumothorax. Gross defect of the chest wall is unavoidable after wide resection of a sarcoma, including chondrosarcoma or osteosarcoma, arising from a thoracic vertebra or rib. If a defect of the chest wall is present, only skin suture following reconstruction of the chest wall by chest patch is acceptable (Fig. 129.6).

The potential risk of inadvertent laceration of the lung during transthoracic approach increases in patients with a past history of chest infection, including tuberculosis.

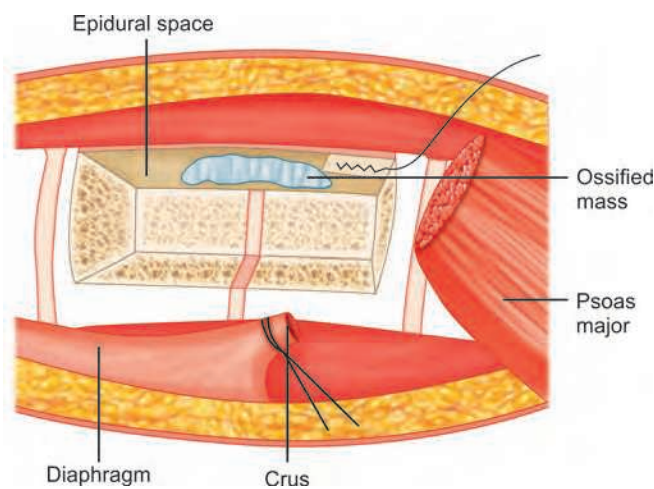
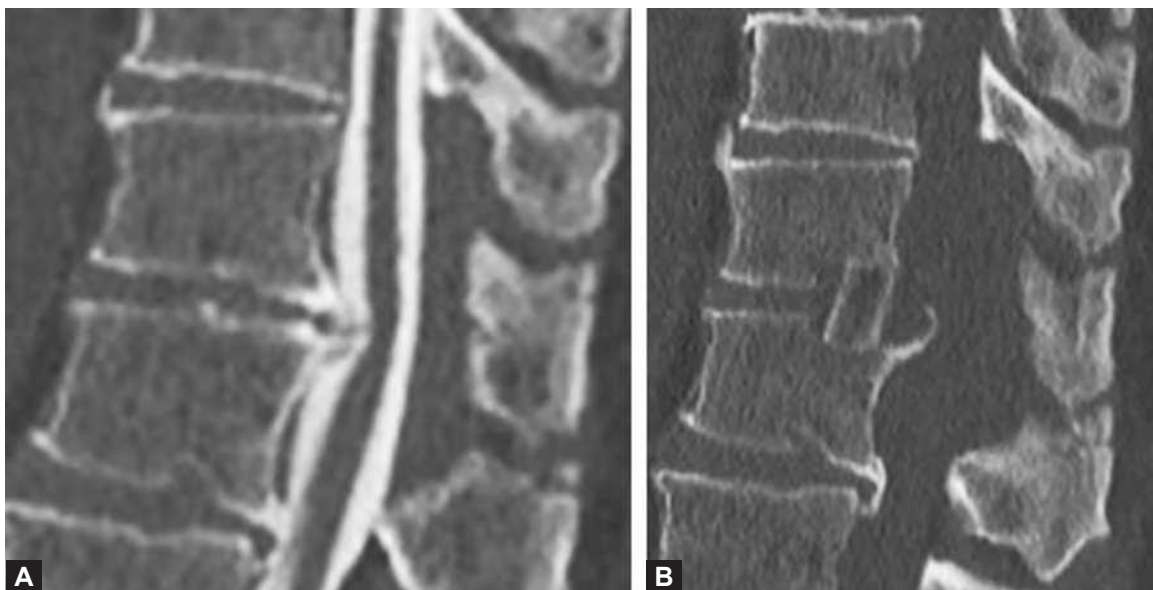


Fig. 129.4: Anterior floating technique of ossification of the posterior longitudinal ligament at the thoracolumbar junction.



Figs. 129.5A and B: Inadequate removal of thoracic ossification of the posterior longitudinal ligament. (A) Preoperative computed tomography (CT) myelography. (B) Postoperative CT.



Fig. 129.6: Reconstruction of the chest wall by chest patch.

For such patients, an extrapleural approach is recommended. For lung injury, direct repair by suturing and covering the injured site with fibrin glue is necessary.

Prevention and Management of Incidental Durotomy

Management of CNS leakage is addressed in another chapter. However, the management of CNS leakage after anterior thoracic surgery has a special aspect, in that leakage spreads into the pleural cavity. In anterior surgery for thoracic OPLL, a consistent method for decreasing the risk of CNS leakage is to avoid complete anterior removal of the OPLL. A direct repair of anterior dural defect after removal of the ossified mass combined with dural ossification is almost impossible. To prevent CNS leakage in anterior surgery for thoracic OPLL, the anterior floating technique of thoracic OPLL after thinning the ossified mass by a diamond burr under microscopy is recommended (see Fig. 129.4). Again, surgeons should remember that removal of the ossified mass may cause excessive bleeding from Batson's venous plexus and/or CNS leakage at the lateral margins of the ossified mass. Placement of fibrin glue is usually ineffective for anterior CNS leakage. If drainage by a chest tube without suction pressure does not fall to <100 mL a day, a drainage system without suction pressure should remain in place. If drainage does not decrease day by day, additional lumbar drainage is an option. The author has experienced cases requiring placement of a chest tube for up to 4 weeks, with no need for surgical repair due to a failure of conservative treatment.

Pleural Cavity Infection

After anterior thoracic surgery, fluid in the chest drain is bloody and/or serous in the normal course of events. Cloudy products, high fever, and elevations in the white blood cell (WBC) count and C-reactive protein (CRP) level indicate pleural cavity infection. Endoscopic debridement and daily irrigation using a double chest tube with intravenous administration of sensitive antibiotics are recommended until the total daily volume of drainage decreases to 100 mL or less and WBC and CRP levels normalize. Before removal of the chest tube, negative results need to be obtained from repeated cultures of drain effluent. When intrapleural infection cannot be conservatively controlled, the worst scenario is wide-open drainage of the chest cavity and open irrigation until good granulation is formed in the chest cavity before delayed closure.

Chylothorax

The thoracic duct lies on the right side of the aorta within the posterior mediastinum. Unrecognized thoracic duct injury can occur during anterior thoracic spine surgery for large spinal tumors arising from the upper thoracic spine, including giant cell tumor, chondrosarcoma, and osteosarcoma. Diagnosis of thoracic duct injury is almost always delayed. Chyle has a variably milky appearance, attributable to its fat content. Watery, creamy fluid in the drainage system suggests thoracic duct injury. Oral feeding should be discontinued and intravenous fluids should be administered along with total parenteral nutrition (TPN) until the leakage of chyle into the drain is almost zero.

COMPLICATIONS OF POSTERIOR SURGERY FOR THE THORACIC SPINE

Spinal Cord Injury

The thoracic spine is naturally kyphotic and decompression laminectomy is theoretically less effective than in the cervical spine. However, anterior removal of the thoracic OPLL in front of the severely compressed and already debilitated spinal cord is extremely dangerous because of the risk of postoperative paraplegia. Posterior decompression with instrumentation has been considered the safest procedure for thoracic OPLL.⁶ However, subtle spinal movement immediately after laminectomy can cause intraoperative spinal cord injury in posterior surgery for thoracic OPLL.⁷

To prevent this complication, temporary instrumentation should be performed before starting decompression procedures.^{6,7} Thoracic ossification of the ligamentum flavum (OLF) frequently coexists with thoracic OPLL. Inadequate decompression also leads to neurological deficit. Preoperative planning by CT and MRI is important to fully complete posterior decompression. Intraoperative navigation and intraoperative ultrasonographic evaluation are useful to confirm achievement of sufficient decompression.⁸

Vascular Complications and Postoperative Epidural Hematoma

Posterior thoracic surgery except for the costotransversectomy approach endangers no major vessels. However, inadequate hemostasis, particularly for small arteries accompanying thoracic spinal roots, can lead to the formation of an epidural hematoma. Epidural hematoma is an avoidable complication of posterior thoracic spine surgery and the risk increases with multilevel extensive laminectomy for thoracic OPLL. Postoperative worsening of paralysis requires emergent exposure for open drainage and hemostasis without MRI investigation. Surgeons should be reminded that repeated hematoma may occur after the first emergent surgery. Delayed epidural hematoma can also occur up to 1 week after posterior decompression surgery for thoracic OPLL in the author's experience. The author recommends placement of suction drainage for around 1 week and prohibition of supine position to decrease pressure on the wound and epidural space.

Total en bloc spondylectomy for malignant spinal tumor only through a posterior approach poses a risk of avulsion injury of a segmental artery from the aorta.⁹ Management of this complication has not been reported in the past and the author has no direct experience of this event, but is aware of cases in which it arose. According to personal communications, an anterior approach after changing the position of the patient while the surgeon pushes on the bleeding site with a finger and assistance from a "superior" cardiovascular surgeon is necessary to manage this trouble.

Intraoperative bleeding due to perforation of the aorta or a segmental artery by a pedicle screw can also be associated with significant morbidity. Placement of intra-aortic stent grafts through the femoral artery after packing the posterior wound is one option for this type of arterial injury.¹⁰



Fig. 129.7: Large spinal pseudomeningocele created by dural tear during previous posterior surgery for ossification of the posterior longitudinal ligament. Surgical closure of a CSF fistula combined with lumbar drainage is required for such a large pseudomeningocele.

Management of Incidental or Intentional Durotomy

Dural ossification is common in patients with OPLL, OLF, or both.¹¹ Ossification of the ligamentum flavum can be posteriorly removed while reserving the arachnoid membrane under microscopic surgery. Resection of the intradural meningioma can be accomplished while reserving the arachnoid membrane.¹² Even with those techniques, CSF leakage can occur. Complete repair of a dural defect after removal of a dumbbell-shaped spinal cord tumor is almost impossible. Thus, even after watertight dural closure, CSF leakage can remain. Placement of fibrin glue is usually ineffective for posterior CSF fistula after posterior thoracic spine surgery. If the drainage does not reduce to <50 mL a day, placement of a drainage system without suction pressure should be retained for >1 week, by which time wound healing of the muscle layer can be expected. Prevention of subcutaneous fistula formation (Fig. 129.7) is a goal of this method. Lumbar drainage remains an option.

Complications of Pedicle Screw Use

Surgeons should be extremely careful during final tightening of pedicle screws not to injure the uncovered spinal cord after laminectomy by mishandling the screw holder. Screw misplacement is the most common complication encountered with thoracic pedicle screw placement. Medial perforation can cause spinal cord injury (Fig. 129.8). Lateral per-

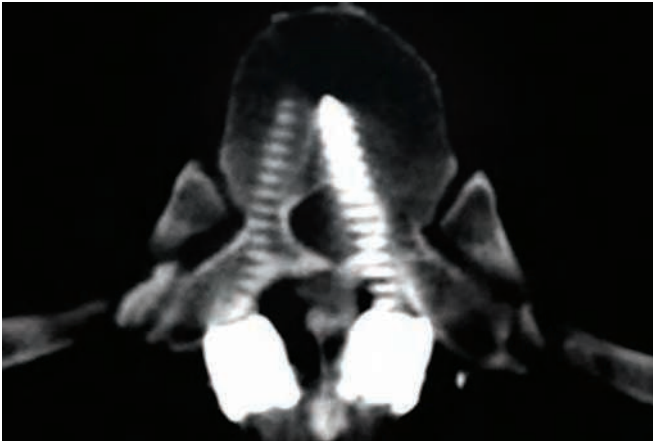


Fig. 129.8: Thoracic pedicle screws placed through the spinal canal. The patient with thoracic ossification of the posterior longitudinal ligament woke up with worsening paraparesis, which was exacerbated following repeat surgery for screw removal.

foration and/or overpenetration by excessive screw length can cause injuries of the aorta or segmental vessels on the anterior surface of the vertebra. Massive bleeding from the aorta or segmental artery is very rare, but if rapidly progressive hypotension occurs during or after surgery, surgeons have to remember this complication and have the ability to call cardiovascular surgeons in to achieve the necessary anterior exploration to cut the perforated screw and repair the injured vessel.^{10,13} An asymptomatic screw in direct proximity to the aorta should be replaced because of the risk of future complications.¹³ Intraoperative detection of a medially perforated screw by portable X-ray is sometimes difficult. Intraoperative CT is useful to allow early revision of a misplaced screw.^{14,15} Although a navigation system is useful, surgical experience and mastery of the technique are crucial to avoid the misplacement of screws.

KEY POINTS

- Spine surgeons should be familiar with the vascular anatomy during anterior thoracic approaches, including transthoracic and sternum-splitting approaches.
- When a major vascular injury occurs, quick consultation with a cardiovascular surgeon is mandatory.
- Spine surgeons should have a detailed knowledge regarding the management of pulmonary complications, including chylothorax.
- Incidental CSF leakage can be managed conservatively.
- Wrong level surgery can be avoided by anticipating difficulties in identifying and radiographically confirming the correct segments.

- Intraoperative fluoroscopy and intraoperative or postoperative CT is helpful to confirm accurate screw placement and decompression.

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Minimally Invasive Surgery and Navigation

Alexander R Vaccaro



Minimally Invasive Endoscopic Cervical Foraminotomy

Anuj Prasher, Bobby Tay

Snapshot

» Anterior Approach

» Posterior Approach

INTRODUCTION

Over the years, the evolution in the treatment of spinal disorders was motivated by enhancing patient outcome by minimizing procedure-related pain and complications, facilitating a quicker return to daily activities, and reducing overall health-care costs. The foundation of many tissue sparing techniques was initially developed to address lumbar-related pathologies and symptoms, and these techniques were adapted and modified for applications in other areas of the spine, including the cervical spine.

One of the earliest publications on cervical spondylosis resulting in posterior cervical disc herniation and spinal cord compression was reported by Bailey and Casamajor¹ in 1911. Mixter and Barr² supported a posterior laminectomy to surgically remove cervical and lumbar disc herniations in 1934, grouping both cervical and lumbar disc herniations together. This approach became the standard of care for the operative management of lumbar and cervical disc herniations for the next decade. In 1943, Semmes and Murphey³ described cervical disc disease associated with radiculopathy as a distinct entity. In time, the consequences associated with cervical laminectomy (postoperative kyphosis, excessive bone and tissue removal, and risk of spinal cord injury) became a significant concern. In the 1950s, both Robinson and Smith⁴ and Cloward⁵ developed the anterior cervical discectomy and fusion in an effort to surgically treat cervical disc disease and spondylosis compromising neural integrity, and to avoid the intraoperative

and postoperative complications associated with laminectomy alone. The anterior approach with discectomy and reconstruction has subsequently been accepted as the utilitarian approach in the treatment of both myelopathy and radiculopathy. Although very safe and very well tolerated by the patient, the anterior dissection is not without pitfalls. To minimize the complications (dysphagia, dysphonia, vertebral artery injury) of an anterior approach, a posterolateral laminoforaminotomy was promoted by Frykholm⁶ in the 1950s and by Scoville and Whitcomb⁷ in the 1960s in the treatment of cervical nerve root impingement. Even further, in an effort to avoid destabilization with a posterior laminoforaminotomy and avoid an anterior discectomy and fusion, an anterior cervical foraminotomy was developed and reported by Verbiest⁸ in 1968. Multiple authors have described variations in this procedure over the next 30 years, including Hakuba,⁹ Lesoin,¹⁰ and Snyder and Bernhardt.¹¹

Over the past 10 years, microendoscopic cervical procedures with a muscle-splitting/sparing approach using tubular retractors and a videoendoscope or operating microscope have been used with good results. These procedures are based on the successful experience and development afforded by prior experience in lumbar spine applications. Endoscopic procedures minimize excessive tissue injury or bone removal, avoid potential destabilization of the spine, decrease postoperative discomfort, allow a quicker return to activities, and minimize hospital stays when addressing cervical spine pathologies (Fig. 130.1). These



Fig. 130.1: The photograph of a 50-year-old woman 3–4 years after a right-sided posterior open foraminotomy. Significant unilateral paraspinal muscle atrophy from local denervation from the surgical approach.

endoscopic procedures can be used for the treatment of foraminal stenosis or a herniated disc in the cervical spine. Roh¹² described an endoscopic foraminotomy performed in cadavers in 2000 using the MED system (Medtronic Sofamor Danek, Memphis, TN, USA). Clinical outcomes using this approach have been promising, attaining a high success rate reported by Adamson,¹³ Burke,¹⁴ Fessler,¹⁵ and Yuguchi.¹⁶ Similar minimally invasive techniques have been used to address cervical pathologies from an anterior approach, as described by Chiu¹⁷ and Fontanella.¹⁸ Furthermore, a cervical microendoscopic decompression for spinal stenosis was developed and reported in 2005 by Perez-Cruet¹⁹ to decrease the morbidity associated with extensive laminectomy or laminoplasty. Such a procedure remains technically challenging due to the constraints of the degenerative spinal canal. Further trials are underway to determine its efficacy versus traditional approaches. Microendoscopic techniques have also been reported for the treatment of odontoid fractures,²⁰ decompression of basilar invagination, high cervical clivus abnormalities, pseudogout granulation mass, and Chiari malformations.²¹ These approaches decrease the opening and resection of the skull base, reducing postoperative complications and speeding recovery.

■ ANTERIOR APPROACH

Minimally Invasive Anterior Cervical Foraminotomy

Minimally invasive anterior approaches are useful techniques in the treatment of cervical radiculopathy through a

transuncal approach.^{22,23} In cases of cervical radiculopathy, a decompression can be done without fusion, preserving the intervertebral disc and completely decompressing the exiting nerve root. Anterior approaches provide direct access to ventral lesions and have the potential for decreased operative time, shortened hospital stay, and no need for implants or immobilization. The indications for minimally invasive anterior cervical foraminotomy are restricted to cervical radiculopathy, but can include bilateral and multilevel foraminal stenosis. Contraindications to this approach are severe central stenosis resulting in cervical myelopathy, aberrant vertebral artery anatomy, ossification of the posterior longitudinal ligament (OPLL), and severe spondylosis. Minimally invasive techniques must also be used with caution in cervical trauma.

Surgical planning²⁴ focuses on an extensive evaluation of the lateral one-third of the motion segment. Preoperative diagnostic imaging should consist of anteroposterior, lateral, oblique, and flexion–extension radiographs of the cervical spine. Advanced imaging such as magnetic resonance imaging (MRI) and computed tomography (CT) scans are useful for delineating the neural/soft tissue and bony anatomy, respectively. There are four key elements to take into consideration when planning an anterior minimally invasive approach. These are the longus colli, uncinat process, vertebral artery, and exiting nerve root. Positioning for surgery is similar to that of a routine anterior discectomy and fusion, with patients in the supine position on a radiolucent table. Excessive extension is avoided during patient positioning. Gardner-Wells traction is not necessary, but traction on the shoulders may be necessary to visualize caudal cervical levels. Intraoperative fluoroscopy is used to mark the initial skin incision, and this is made in a skin crease when possible. A standard Smith-Robinson approach is used to expose the pathologic side causing radiculopathy. The lateral third of the vertebral column is identified with the elevation of the longus colli muscle using a Penfield-1 and a microbipolar. Retractors are placed in the usual manner, deep to the longus colli muscles. The medial and lateral margins of the uncinat process are identified and exposed using Kittner dissection and a Penfield-4. Full exposure is achieved when the uncinat process and lateral thirds of the cranial and caudal vertebral bodies and disc are visualized. It is recommended to perform the remainder of the procedure with an intraoperative microscope, as loupe magnification may not provide sufficient magnification or illumination. A Penfield-4 is used to expose the lateral border of the uncinat process of the caudal vertebral body along a plane

between the vertebral artery and the uncinat process. The concave side of the Penfield-4 should be placed along the uncinat process's lateral margin, protecting the vertebral artery from iatrogenic injury. The uncinat process is then resected using a long-handled high-speed drill using a 2.2/2.3 mm matchstick burr (Midas Rex Legend, Fort Worth, Texas/Anspach, Palm Beach Gardens, FL, USA). Five to six millimeters of bone is drilled away, maintaining a 1–2 mm thick margin of bone between the drill and Penfield-4. Frequent saline irrigation is encouraged along with use of bone wax for bleeding cancellous bone. Drilling is continued in a cephalad direction toward the nerve root posteriorly, along with fluoroscopic guidance to identify trajectory and depth. Drilling straight posteriorly will lead to the superior pedicle margin and away from the neuroforamen. The posterior longitudinal ligament (PLL) is identified, and a plane is developed between the PLL and the posterior aspect of the vertebral body. Cervical Kerrison rongeurs (Aesculap, Tuttlingen, Germany), 1.0-, 1.5-, or 2.0-mm, are used to remove remaining bony elements, osteophytes, cartilage, periosteum, and PLL. The lateral margin of the uncinat process is removed by a Penfield-4 by using a lateral to medial “sweep” to fracture remaining bone from the vertebral body. Some authors prefer to leave this shelf of bone to protect the vertebral artery.²⁵ However, when doing this, care must be taken to determine that the remaining bone will not cause persistent compression of the exiting nerve root. Meticulous hemostasis is critical, using a combination of bipolar cautery, gelfoam powder, and Floseal (Baxter Health Care Corporation, Deerfield, IL, USA) or Surgifoam (US surgical). The path of the nerve root is visualized and decompressed medially from its origin from the spinal cord and laterally to the area posterior to the vertebral artery. A blunt microneur hook can be passed along the course of the nerve to ensure all disc fragments have been removed and an adequate decompression has been performed. A drain may or may not be used.

Minimally Invasive Anterior Cervical Corpectomy

A minimally invasive anterior approach can also be used for central corpectomy to treat OPLL.²⁶ Traditional anterior approaches for corpectomies afford a direct approach to decompression of the spinal canal.²⁷ However, it can also result in postoperative kyphotic changes,^{28,29} increased blood loss, and potential for implant related complications. Hirano et al. has described a minimally invasive

central corpectomy (MICC) for the treatment of cervical segmental ossified PLL, which includes reconstruction with a cylindrical titanium cage containing autologous local bone graft. The indications for MICC are limited to OPLL within two disc levels. Corpectomy should not be more than half of the vertebral body height to avoid early vertebral settling and progressive kyphosis due to graft settling. Contraindications include severe osteoporosis, patients on hemodialysis, and smokers. The characteristics of the OPLL and dural ossification are extremely important when considering MICC.³⁰ The OPLL with extensive lateral extension is inaccessible via the MICC window, and OPLL adherent to the dura poses a significant risk for CSF leak. If the above criteria are not met, a traditional corpectomy or a posterior-based approach should be the treatment of choice to avoid significant complications. In cases where the OPLL is adherent to the underlying dura, “floating” the ossified portion is an acceptable option. Minimally invasive central corpectomy should be an option only in cases with segmental, small continuous or mixed type of OPLL, and without adhesion of the OPLL with the adjacent dura.

The procedure includes upper- or lower-half central corpectomy of the involved cervical vertebral body, transdiscal decompression of the adjacent disc level, dissection and removal of the OPLL behind the vertebral body, and instrumentation/fusion with a cylindrical titanium cage. As described by Hirano et al., anterior plate fixation is not necessary. Care must be taken to preserve the bony end plates to avoid early subsidence of the cage. Postoperatively, patients are immobilized with a soft cervical collar for 1 week, and patients are followed at routine intervals.

POSTERIOR APPROACH

Minimally Invasive Posterior Cervical Foraminotomy

Posterior approaches to the cervical spine are an essential tool for a spine surgeon for the treatment of various pathologies. Posterior cervical laminoforaminotomy continues to be an effective option to treat radiculopathy caused by foraminal stenosis or lateral herniated discs, with success rates ranging from 92% to 97%.^{31,32} In patients with cervical spondylotic myelopathy, reported rates of neurologic improvement vary from 63% to 83%^{33–36} with a posterior decompression either in laminectomy or laminoplasty. Posterior-based procedures also do not carry the risk of recurrent laryngeal nerve paralysis, esophageal injury, dysphagia, dysphonia, vascular injury, and adjacent segment

disease.^{37,38} Traditional open posterior approaches require extensive soft-tissue stripping of the paraspinal musculature, which can lead to significant pain, disability, and weakness with neck extension (especially if the extensor attachments at C2 and C7 are disrupted). Posterior approaches without fusion also have a limited role in patients with cervical kyphosis. The fundamental idea behind tissue-sparing techniques in the cervical spine is to minimize approach-related soft-tissue injury, pain, and dysfunction. With the development of sequential dilation of muscle fibers and tubular retractor systems with specialized instrumentation and improved endoscopic equipment, minimally invasive procedures can be used safely for posterior cervical decompressions.

A cervical microendoscopic laminoforaminotomy was first described in a cadaver model to demonstrate its feasibility. The procedure was a direct evolution from the application of tubular retractor systems in the lumbar spine for discectomy and decompression. The technique was shown to have equivalent nerve root decompression and bony resection as traditional open approaches (Burke,¹² and Roh¹⁴). In clinical application, the microendoscopic procedures have reported similar success rates as compared to their open counterparts.³⁹ As expected, the less invasive approach has less blood loss, postoperative pain, and shorter hospital stays as compared to the open procedure. Gala et al.⁴⁰ reviewed clinical outcomes in patients undergoing a cervical microendoscopic foraminotomy/discectomy and found statically significant improvements in mean visual analog scale scores for headache, neck pain, and arm pain compared to their preoperative levels. Mean neck disability index scores also showed a significant improvement, as short form 36 scores also showed improvement in the bodily pain, physical function, and role limitations due to physical problems subscales. There is a theoretical decreased risk of developing iatrogenic kyphosis due to preservation of the native osteoligamentous anatomy of the cervical spine especially the posterior ligamentous complex. The indications for a cervical microendoscopic laminoforaminotomy include one and two level unilateral foraminal stenosis, residual radicular symptoms after anterior cervical discectomy and fusion, and radiculopathy caused by cervical disc disease, where an anterior approach is contraindicated (previous radiation, tracheostomy, etc.). Contraindications include gross instability, significant ventral compression (OPLL), severe central stenosis or central disc herniation, cervical myelopathy, kyphotic deformity, and axial neck pain without radicular

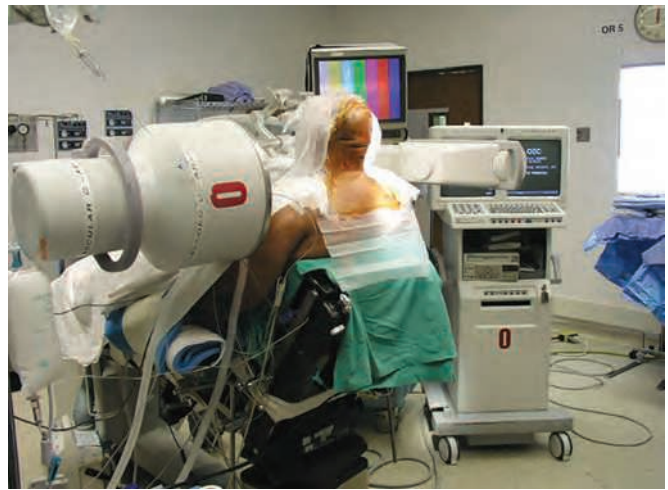


Fig. 130.2: Patient positioning in the sitting position for posterior endoscopic foraminotomy. Fluoroscope is placed to provide a lateral view of the cervical spine. Video monitor is placed over the arm of the fluoroscopic unit.

symptoms. Proper preoperative evaluation consists of a thorough history and physical, as well as MRI (or CT myelogram if unable to obtain MRI) and cervical spine X-rays (anteroposterior, lateral, and flexion-extension views). Electromyography (EMG) may be useful to distinguish a peripheral nerve entrapment from a cervical radiculopathy. Diagnostic selective nerve root blocks, if effective, increase the potential for a good outcome after decompression. The equipment needed for this procedure is a Mayfield (Integra LifeSciences, Plainsboro, NJ, USA) device compatible with a semisitting position, a tubular retractor system with an endoscope, an endoscopic monitor with camera, cervical Kerrison rongeurs (1.5 and 2 mm), microcervical bayonnetted curettes, a high speed drill, and intraoperative fluoroscopy.

The procedure can be done in the sitting or the prone position (Fig. 130.2). The sitting position offers several advantages including less bleeding at the site of decompression and better radiographic imaging of the cervical spine allowing for more accurate placement of the tubular retractors while minimizing the skin incision. Neuro-monitoring (somatosensory-evoked potentials, EMG, or transcranial motors), arterial lines, and Foley catheters are not routinely used. Neuro-monitoring may be used in cases of severe cervical stenosis which is a relative contraindication to performing a foraminotomy alone. Precordial Doppler may be useful to detect air embolism, although with a small exposure this risk is low. The relative incidence of asymptomatic air embolus is thought to be 1:2,000. The semisitting position affords decreased blood pooling in



Fig. 130.3: The lateral fluoroscopic view of the cervical spine with the first dilator docked at the facet joint of C7-T1 that can be easily imaged with the patient in the sitting position.

the operative field, reduced blood loss, shorter operative times, and provides improved lateral fluoroscopic images because of the gravity-dependent position of the shoulders. The neck is slightly flexed, and the Mayfield clamp is attached to the table mounted cross-bar. The C-arm is brought in and adjusted to obtain a perfect lateral image of the cervical spine. The fluoroscopy screen is placed usually to the right of the surgeon, and the endoscopic monitor is placed in front of the surgeon. The operative levels are reconfirmed with intraoperative fluoroscopy, and a skin incision is marked, approximately 16–18 mm in length 5–10 mm from midline toward the symptomatic side. In cases where more than two levels are symptomatic, a staged decompression is a better approach to decrease operative times and allows the patient to still go home the same day. A straight Kelly clamp is used to spread down to the lamina-lateral mass junction. Use of guidewire is contraindicated in the cervical spine as inadvertent penetration into the spinal canal can occur with disastrous consequences. Even with the Kelly clamp, care must be taken to avoid entering the interlaminar space. The initial dilator is then docked at the lamina-lateral mass junction at the lateral edge of intralaminar space (Fig. 130.3). Sequential dilation is performed until a 16 or 18 mm tubular retractor is in place. The position of each dilator is confirmed with lateral fluoroscopy. Once the tubular retractor is in place, it is attached to the table mounted flexible arm, and the dilators are removed. A 25° endoscope is inserted into the tube to visualize the bottom of the field (Fig. 130.4). Pituitary rongeurs are used to remove any muscle in the

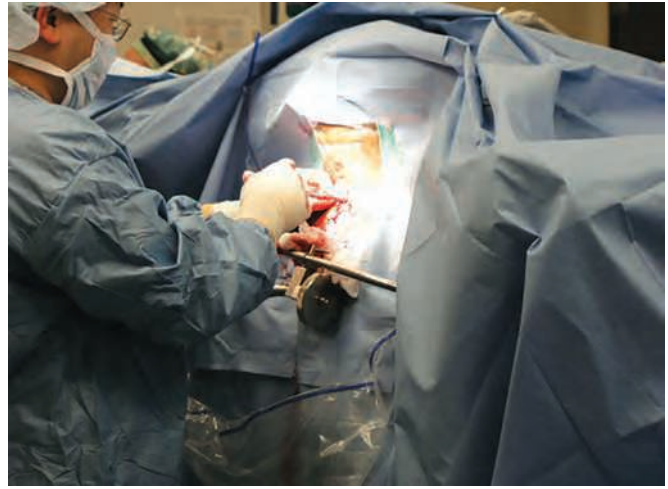


Fig. 130.4: A 16-mm tubular retractor is docked on the lamina–facet junction of the targeted level and secured to a mechanical arm. A 2.5-mm glass endoscope attached to a three-chip video camera using a custom C-mount allows visualization of the anatomic structures in high magnification.

operative field, and straight and angled bipolar forceps are used for hemostasis. A microcervical curette is used to further delineate the anatomy of the inferior edge of the rostral vertebrae and the corresponding lateral mass (Fig. 130.5). A high-speed matchstick burr is then used to start the laminoforaminotomy by removing the inferolateral edge of the lamina of the rostral vertebrae, followed by the medial edge of the lateral mass. This exposes the superomedial one-third of the superior facet of the caudal vertebra that is further thinned down with the burr (Fig. 130.6). Care must be taken to preserve at least 50% of the facet joint to avoid instability.⁴¹ The ligamentum flavum is then removed to expose the lateral edge of the dura and proximal portion of the nerve root. A 1.5 or 2 mm Kerrison rongeur can then be used to complete the laminoforaminotomy safely, decompressing from the medial border of the caudal pedicle to the lateral border of the caudal pedicle (Fig. 130.7). Dural pulsations can be seen in the nerve root sleeve after sufficient decompression. A 2-0 angled curette can then be used to decompress the exit zone of the foramen. A methylprednisolone-soaked piece of Gelfoam may be placed over the nerve root to reduce postoperative inflammation (Figs. 130.8 and 130.9). Early mobilization is encouraged, and no cervical immobilization is necessary. Generally, patients can be discharged to home after 2–3 hours if medically stable (Fig. 130.10). Postoperative medications include a narcotic analgesic with acetaminophen and a muscle relaxant.



Fig. 130.5: The intraoperative view of the C7 lateral mass and lamina.



Fig. 130.6: The intraoperative view of the shoulder of the C8 root and the superior facet of T1 that has been thinned down with a 2.2 mm matchstick burr.



Fig. 130.7: The intraoperative view of the C8 root after complete decompression over the medial and lateral borders of the T1 pedicle.



Fig. 130.8: The intraoperative view of the muscular split as the tubular retractor is slowly withdrawn.

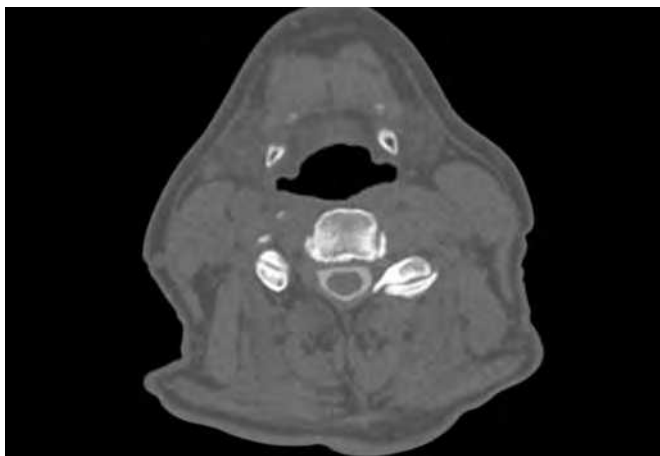


Fig. 130.9: The postoperative axial CT image after right C7-T1 foraminotomy.



Fig. 130.10: Healed incision after endoscopic laminoforaminotomy.

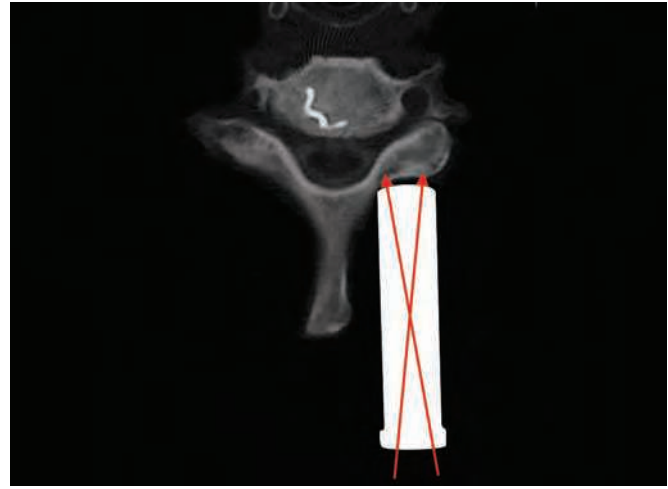


Fig. 130.11: The tube is initially angled toward the lateral mass to perform the foraminotomy.

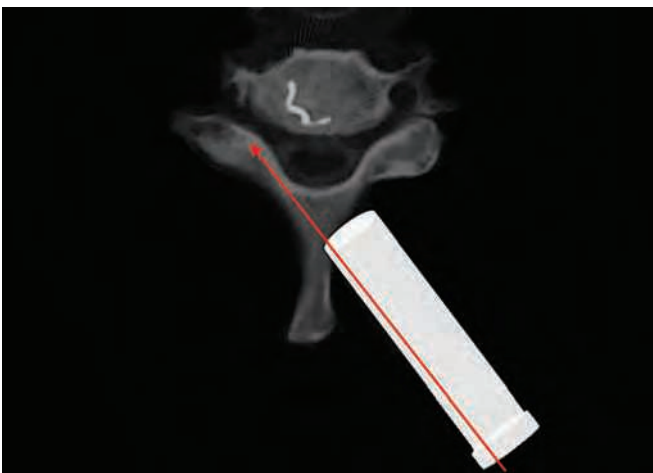


Fig. 130.12: After the foraminotomy is completed, the tube is then angled medially to allow resection of the ipsilateral lamina and the undersurface of the contralateral lamina.

Complications of the cervical endoscopic approaches include infection, CSF leak, air embolism and neurologic complications. The risk of infection and CSF leak are most common, ranging from 1%¹³ to 8%.¹⁵ Because the operative field is narrow, small inadvertent durotomies can be treated by simply covering the defect with muscle, fat, Gelfoam, dural substitute followed by fibrin glue or synthetic sealants followed by bed rest for 24 hours. For larger tears, a lumbar CSF drain may be necessary for 2–3 days. Post-operative pseudomeningoceles and CSF-cutaneous fistulas are rare due to the lack of dead space and small incision.

Venous air embolism may occur during any operative procedure in which the operative site is above the level of

the heart. Venous air embolism of some degree is detected in all patients undergoing neurosurgical procedures such as craniotomy in the sitting position.⁴² This sets up a condition of negative venous pressure relative to the atmosphere, which favors the passage of air into the circulation. However, these procedures tend to expose a large surface of exposed bone and dura to air in contrast to the minimal bony exposure in endoscopic cases. Gala et al.⁴⁰ have no reported cases of venous air embolism. Potential neurologic complications include nerve root injury from decompression or manipulation and direct spinal cord compression during docking, dilation or decompression.

Microendoscopic Cervical Decompression for Spinal Stenosis

Gala et al.⁴⁰ also describe a cervical microendoscopic decompression of stenosis. After the ipsilateral laminotomy is completed, the ligamentum flavum is left in place to protect the dura (Fig. 130.11). The endoscopic tube is angled toward the contralateral side, and a subligamentous plane is dissected along the undersurface of the spinous process. A high-speed burr with a guard sleeve extended is then used to progressively remove the bony undersurface of the spinous process and contralateral lamina across to the contralateral facet (Fig. 130.12). This avoids any downward pressure on the dura and spinal cord. The ligamentum flavum may now be removed with curettes and Kerrison rongeurs. Once there is adequate decompression, the tube is directed to its original position to remove the ipsilateral ligament and bone, which will reveal a completely decompressed thecal sac (Fig. 130.13).

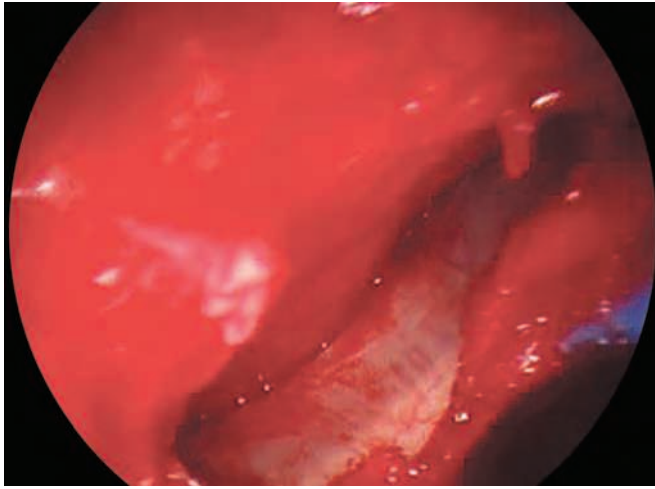


Fig. 130.13: The view of decompressed spinal canal and dural sleeve after microsurgical laminoplasty.

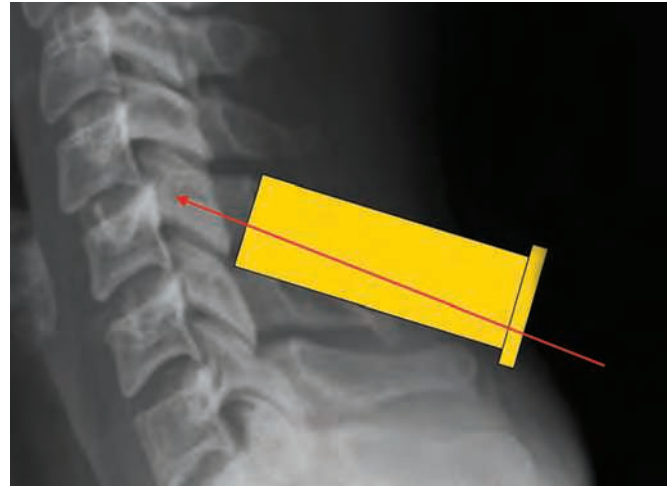


Fig. 130.14: The tube is placed 20° cephalad to dock onto the lateral mass to allow appropriate angulation for instrumentation.

Minimally Invasive Posterior Lateral Mass Instrumentation and Fusion

Mikhael et al.⁴³ describe posterior instrumented fusion using lateral mass screw placement and bilateral foraminotomy through an endoscopic tubular approach. The indications for minimally invasive lateral mass screw placement for posterior cervical arthrodesis are instability from C3 to C7, fusion for prior posterior cervical laminectomies, or in conjunction with anterior corpectomy and fusion using strut grafting. Lateral mass screw placement is contraindicated in patients with lateral mass hypoplasia, lateral mass fracture or aberrant vertebral artery anatomy, making lateral mass screw placement difficult or impossible. The procedure is performed through a midline vertical incision in line with the spinous processes. This incision is usually 3–4 cm long to accommodate the tubular retractors. The incision is centered over the pathologic level for single-level procedures, and should be centered one level above the most inferior surgical level when performing multilevel procedures. The underlying fascial incision is also 3–4 cm in length and is made 4–6 mm off of midline toward the pathologic side. If a bilateral arthrodesis is being performed, two separate fascial incisions are made. Soft tissues are bluntly dissected until the lateral mass and facet joint of interest can be palpated. A dilator is then placed over the facet joint in a trajectory 15–20° cephalad to stay in-line with the path for screw placement, and the level is confirmed with intraoperative fluoroscopy. Serial dilation is used in the same manner as described previously, maintaining the identical trajectory, and the tubular retractor is placed (Fig. 130.14). The lateral mass and

facet capsule can now be fully exposed. A skirted retractor can be used for deeper retraction over multiple levels. It is critical to maintain the 15–20° of cephalad angulation with complete visualization of the medial and lateral borders of the lateral mass for proper instrumentation. Caution must be exercised during exposure to avoid violating the facet capsules that are not to be fused. The starting point for the lateral mass screw is in the middle of the lateral mass in the cranial-caudal plane and 1 mm medial to the midline in the medial-lateral plane. This starting point can be marked by creating an indentation in the cortex using the 2 mm matchstick burr. A 2.5 mm drill 14 mm in length is then placed at the starting point and oriented approximately 15–20° cephalad and 30° in a medial to lateral direction, parallel to the slope of the facet joint (Fig. 130.15). This orientation avoids drilling into the facet joint, avoids the nerve root inferiorly, and avoids the vertebral artery, typically in the midline of the lateral mass. A ball-tipped probe is then inserted into the hole to palpate for a breach, followed by a tap, probe, and 3.5 mm screw. These steps are repeated at subsequent levels. Intraoperative fluoroscopy is then used to confirm proper placement of instrumentation. The rod can then be engaged to the screws with a pivoting inserter. Complications with this approach arise when there is inadequate visualization of the lateral mass. If the proper trajectory cannot be determined, or if the anatomic landmarks are obscured, conversion to an open approach may be necessary. Complications associated with improper screw placement are vertebral artery injury, nerve root injury, poor fixation, and violation of the facet joint leading to postoperative pain.

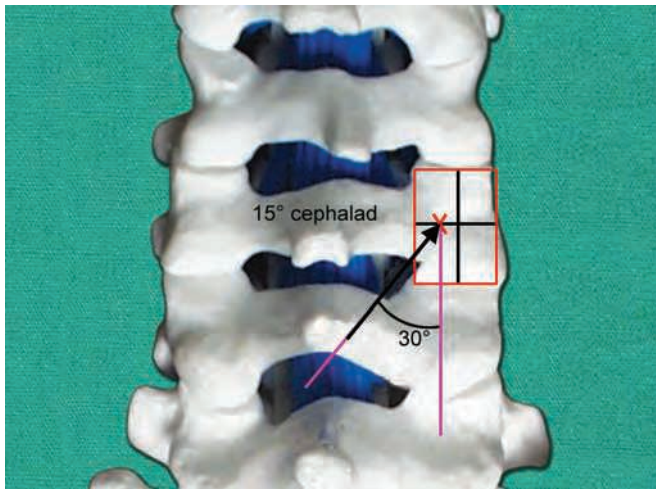


Fig. 130.15: The trajectory of the lateral mass bone screw is 15–20° cephalad and 30° of lateral angulation.

Minimally Invasive Cervical Laminectomy and Laminoplasty

The clinical application of minimally invasive multilevel decompressions (laminectomy and laminoplasty) has not been well-studied. Significant technical challenges exist when performing minimally invasive laminoplasty, including difficulty with elevation of the lamina and insertion of bone grafts. Perez-Cruet¹⁹ and Wang³⁶ examined the feasibility of minimally invasive multilevel laminoplasty and laminectomy in cadaver models, showing it is possible to expand the cross-sectional area of the spinal canal by 43%. Minimally invasive approaches in general must provide at least equivalent patient outcomes when compared with traditional open procedures. As techniques improve, the ability to treat increasingly complex problems of the cervical spine *via* minimally invasive means will most likely continue to grow.

Management of Inadvertent Durotomies

Inadvertent durotomy is one of the most common complications in spine surgery. Unrecognized or improper treatment of durotomies can lead to postural headaches, back pain, nausea, and more serious consequences such as pseudomeningocele formation, cutaneous CSF fistula,⁴⁴ intracranial hemorrhage, meningitis, and neurologic deficit. The rates of pseudomeningocele formation and cutaneous CSF fistulas/persistent CSF leaks are believed to be lower in minimally invasive approaches due to the decreased dead space from smaller incisions and muscle-splitting approaches.⁴⁵

Ruban and O'Toole⁴⁶ developed a treatment algorithm for the treatment of inadvertent durotomies in minimally invasive spine surgery. All patients with partial thickness durotomies and intact arachnoid were treated with fibrin glue only. For full-thickness durotomies, a primary repair was attempted. Dorsal or dorsolateral durotomies were typically repaired primarily using interrupted 4-0 Nurulon (Ethicon) sutures. If the repair was not watertight to a Valsalva maneuver, a small piece of locally harvested paraspinous muscle was sutured to cover the defect. Fibrin glue was then applied over the repair, whether it was watertight or not. Durotomies located at the lateral edge or undersurface of the bony window, or on the ventral surface of the dura, are virtually impossible to repair. For these cases, a small blood-soaked piece of Gelfoam was laid over the dural defect, followed by application of fibrin glue. Once the fibrin glue was allowed to congeal, the minimal access retractor was slowly removed, and meticulous hemostasis was obtained by bipolar cauterization. The fascia was then closed with 0-Vicryl sutures in an interrupted fashion, followed by 2-0 Vicryl for the subcutaneous layer, followed by Dermabond (Ethicon). No drains were used. The patients were kept on strict bed rest overnight and were allowed to fully mobilize the next morning. No additional antibiotics were administered. In this case series, no patient developed a postoperative cutaneous CSF fistula or pseudomeningocele. No patient complained of persistent headaches or nausea, and there were no new neurological deficits attributable to durotomy after surgery. Of note, a commercially available, specialized set of dural repair instruments was used that includes two modified needle drivers and a bayoneted Chitwood Knot Pusher (Scanlan International, St. Paul Minnesota).

Minimally invasive procedures are usually performed through tubular retractors, making dural repair difficult. These small tubes limit the use of traditional instruments used for dural repair, especially for opening and closing the instruments as well as achieving the proper angulation. Chou et al.⁴⁷ described a technique to circumvent this difficulty using commonly available instruments in the operative room for primary dural closure. Using a standard micropituitary rongeur, 5-0 Prolene suture (Ethicon Inc, Somerville, NJ, USA), and a laparoscopic knot pusher, primary dural repair can be performed.

The U-Clip (Medtronic, Minneapolis, MN, USA) can also be used to assist in primary closure of durotomies in minimally invasive spine surgery. Song and Park⁴⁸ described a technique to close durotomies and examined the performance of the U-Clip for the closure of inadvertent durotomy occurring during minimally invasive spine

surgery. The U-clip is a novel device that can achieve tight tissue approximation without the need for knot-tying and excessive suture manipulation, making it an ideal tool to use in minimal access surgery. The U-Clip is a self-closing nitinol clip attached to a conventional surgical needle by a flexible suture-like member. It was initially designed for coronary artery anastomoses, as it allows for tight tissue reapproximation without the need for knot-tying and excessive suture manipulation.⁴⁹ When a durotomy occurred, the edges of the dura were identified, reapproximated, and repaired primarily using one or more U-clips in an interrupted fashion. The U-clip is then positioned across the dural edges appropriately, and a bayoneted needle driver is used to compress the “release sleeve” that attaches the U-Clip to the flexible member, deploying the clip. After detachment, the U-Clip reshapes itself from a U-shape into a closed loop. When more than one U-Clip was needed to close the durotomy, the U-clips were placed at 2 mm intervals in an interrupted fashion. All patients were mobilized immediately, and out of seven patients, six were discharged as outpatients. No patients in this study had clinical symptoms of a CSF leak at follow-up, and all incisions healed without evidence of wound infection or pseudomeningocele.

Minimally Invasive Tumor Resection

Spinal tumors are relatively rare lesions, occurring with an incidence of 1–2/100,000.⁵⁰ Two-thirds are extramedullary, either intra- or extradural.⁵¹ Schwannomas, neurofibromas, and peripheral nerve sheath tumors make up 40% of extramedullary lesions, meningiomas an additional 40% and filum ependymomas 15%.⁵² Intramedullary lesions can be of glial origin (ependymomas and astrocytomas), and hemangioblastomas, metastases, other glial tumors, and benign lesions are also seen.⁵³ The clinical presentation of spinal tumors is consistent with a slow growing mass. Patients may initially present with neck pain, radiculopathy, and myelopathy depending on tumor size and location. The diagnosis is usually confirmed by MRI. The treatment for all extramedullary tumors is complete surgical excision. For intramedullary tumors, gross total excision is attempted without causing iatrogenic neurologic compromise. The traditional procedure requires a midline incision, muscle stripping, and multilevel laminectomy to provide access to the tumor. Minimally invasive techniques aim to limit the extent of tissue destruction/dissection, while achieving the same surgical goal, avoiding the incidence of iatrogenic instability. These minimally invasive approaches may reduce postoperative pain, reduce blood

loss, speed recovery, shorten hospital stay, and maintain spinal structural integrity.

Haji et al.⁵⁴ describe a surgical technique for the resection of intramedullary, intradural extramedullary, and extradural spinal neoplasms using a tubular retractor. In their series, only two patients had cervical tumors. One was a 54-year-old male with a C6 intradural atypical meningioma (WHO Grade II) and a 72-year-old female with a C5–C6 intradural meningioma. The patient with the C6 lesion had worsening of his symptoms after surgery, however had improved to baseline at the time of discharge, and noticed significant improvement by 6 weeks postoperative, with some residual distal extremity weakness and hyper-reflexia. The patient with the intradural meningioma had complete resolution of weakness, persistent upper extremity hyper-reflexia, and diminished lower extremity position sense with left foot numbness. Mannion et al.⁵⁵ reported safe removal of intradural extramedullary tumors using a minimally invasive approach. A C6–C7 meningioma was removed from a 47-year-old female without complications. She was mobilized after 24 hours and was discharged home 2 days postoperatively. In their series, the minimally invasive approach was comparable to open surgery, without postoperative morbidity related to the approach. Zhang et al.⁵⁶ retrospectively reviewed 39 consecutive patients who underwent cervical intraspinal extramedullary tumor resection. These patients were divided into two groups, those undergoing a unilateral laminectomy or a partial unilateral laminectomy, and those undergoing a standard laminectomy. They reported positive clinical outcomes for the treatment of cervical intraspinal extramedullary tumors with a minimally invasive approach, including shortened operation time, decreased intraoperative blood loss, preservation of ligamentous and bony structures, and likely a reduced deformity rate. At 2 years follow-up, no patient in the hemilaminectomy or hemi-semi-laminectomy group had developed deformity.

The indications for a minimally invasive approach for the resection of spinal tumors have not been thoroughly evaluated. Contraindications include situations where dural resection is desired to achieve a complete resection, as the minimally invasive surgical window may not allow appropriate duraplasty to achieve a watertight closure. Tumors extending across more than two spinal levels are too large to be resected through a single MIS approach. One and two level extradural/intradural extramedullary spinal neoplasms can be resected through a MIS window without an increased risk for adverse neurologic complication. Minimally invasive surgery for the removal of tumors

will only have utility when the same surgical goals can be achieved despite a smaller surgical window, the risks of surgery to the patient are no greater than a traditional open approach, and that these techniques offer an advantage over open procedures.

Kypho- and vertebroplasty are widely accepted for treating patients with pathologic thoracolumbar lesions. These procedures can provide rapid pain relief and restoration of spinal stability. A transpedicular approach can be risky due to the anatomy of the cervical spine. A minimally invasive approach for anterior cervical kyphoplasty has also been described in the literature by Disch et al.⁵⁷ A C2 and C5 kyphoplasty was done using one minimally invasive anterior approach through a small incision. The procedure went uneventfully, and provided immediate pain relief and patient mobilization. Three-month follow-up showed an excellent outcome. In the future, kyphoplasty via a minimally invasive anterior approach may be a feasible, successful, and safe surgical method in the palliative treatment of metastatic disease.

KEY POINTS

- Minimally invasive foraminotomy is an excellent alternative to anterior cervical discectomy in the treatment of unilateral radiculopathy due to foraminal disc herniation or foraminal stenosis from cervical spondylosis.
- Posterior cervical foraminotomy does not consistently treat motor weakness from foraminal compression that is not associated with pain.
- Anterior cervical foraminotomy requires good preoperative planning to locate the position of the vertebral artery prior to decompression.
- Anterior cervical foraminotomy is more effective in cases of significant anterior spurs and in cases of posterolateral disc osteophyte complexes causing spinal stenosis.
- An operating microscope or endoscope is necessary in both procedures to enhance the visualization in the operating field.

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Minimally Invasive Techniques of the Thoracic Spine

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Snapshot

- » Indications
- » Patient Evaluation
- » Positioning
- » Technique for Transthoracic Thoracoscopic Approach
- » Considerations and Complications of Thoracoscopy
- » Technique for Mini-open Lateral Retropleural Approach
- » Considerations and Complications of Mini-open Lateral Retropleural Approach
- » Outcomes

INTRODUCTION

Thoracic spine disease due to its anatomical constraints has historically posed a dilemma when choosing a surgical approach. A variety of anterior and posterior open techniques have been previously described. Thoracic laminectomies were used historically with poor results due to spinal cord manipulation.¹ Posterior approaches to the thoracic spine include the transpedicular, costotransversectomy, and lateral extracavitary approaches. All of these approaches typically only allow a very limited working window.²⁻⁷ Anterior approaches were later developed to allow direct access to the vertebral column. Commonly used anterior approaches include transthoracic and lateral retropleural thoracotomy; however, approach-related morbidity is still high.⁸⁻¹⁰ Anterior approaches require double-lumen intubation with single-lung ventilation during the procedure as well as postoperative chest tube drainage.¹¹ Open approaches have demonstrated increased rates of infection, intercostal neuralgia, post-thoracotomy pain syndrome, diaphragmatic injury, and pulmonary complications.^{12,13} Post-thoracotomy pain syndrome has been reported in up to 50% of patients.¹⁴ In the early 1990s, McCormick popularized the lateral retropleural approach to the anterior thoracic spine.¹⁵ In order to minimize the

approach-related morbidity, minimally invasive techniques have been developed.

Minimally invasive surgical (MIS) techniques have been present for decades, but their application to the thoracic spine has only recently become popular.¹⁶ Thoracoscopic surgery was first performed in the early 1990s in order to complete vertebral biopsies, thoracic discectomies, and thoracic sympathectomies.^{17,18} Despite limited data, early reports on both thoracoscopic and MIS techniques have found comparable clinical outcomes to traditional open procedures.¹⁹ Benefits of muscle-sparing approaches include diminished blood loss, expedited recovery, less postoperative pain, and decreased hospitalization.^{8,9,19,20}

INDICATIONS

Minimally invasive surgical and thoracoscopic indications are the same as for traditional open approaches to the thoracic spine. Thoracic discectomy and corpectomy is indicated in cases of infection (e.g. osteomyelitis or spondylodiscitis), primary or metastatic tumors, unstable fracture patterns, and large symptomatic disc herniations.^{20,21} The mini-open lateral retropleural or anterolateral thoracoscopic approach for corpectomy and fusion are ideally

suited for 1–2 level procedures.^{15,22} The superior anterior thoracic spine remains a difficult region to access as the scapula limits a lateral approach and the superior mediastinum obstructs an intrathoracic approach.^{20,23} Abduction of the arm by 90–110° may allow lateral access as high as T3.¹¹

PATIENT EVALUATION

Evaluation of a patient for a minimally invasive discectomy and corpectomy should focus on the nature and location of the patient's complaints as well as comorbidities. Preoperative pulmonary function is critical to address as pre-existing lung disease may lead to significant complications. Patients with pre-existing pulmonary conditions may benefit from an extracavitary approach as single-lung ventilation is not routinely used.²⁰ A history of a prior thoracotomy, chest trauma, chest tube placement or thoracic spine surgery may relegate a minimally invasive approach unfeasible due to significant scarring or pleural adhesions.⁸

Patients may present with signs of axial discomfort, radiculopathy, and/or myelopathy.²⁴ Neurological examination focusing on sensory levels and lower extremity motor strength is essential for patients with thoracic spine pathology. Rectal tone should be assessed and sacral sparing identified if there is any neurologic deficit.

Preoperative evaluation focuses on the vertebral level of the disease and its relationship to the vasculature.¹⁸ Location of the heart, great vessels, and diaphragm play a role in choosing the laterality of the approach. In the upper thoracic spine, a right-sided approach is preferred, thereby avoiding the aortic arch and descending aorta. The diaphragm, liver, and inferior vena cava are at risk at lower levels, and therefore, a left-sided approach is preferred. The proximal thoracic spine is inaccessible via an MIS approach due to the mediastinum, scapula, and shoulder girdle, limiting access to the vertebral bodies of T1–T3.^{11,20}

POSITIONING

The lateral decubitus position is preferred for both MIS and thoracoscopic approaches (Fig. 131.1). Laterality of the approach depends on the location of the pathology. A right-sided approach (left lateral decubitus) may be easier to gain access to T4–T9 vertebrae by avoiding the mediastinal structures. A left-sided approach (right lateral decubitus) is preferred for access to T10–L2 as the aorta is easier to mobilize than the inferior vena cava.^{11,25} The patient is positioned such that the break in the table is at the



Fig. 131.1: Lateral decubitus positioning on a Jackson table.

operative level. A bump is also placed at the affected level to allow maximal flexion.²⁶ An axillary roll is placed to avoid brachial plexopathy and the arms are flexed forward. The knees and ankles are well padded to relieve pressure to the peroneal nerve and malleoli. The pelvis and upper thorax are taped to allow flexion without moving the patient.²⁶ The surgeon is positioned dorsally and the fluoroscopic C-arm and mounted retractor arm are ventral to the patient. The tubular retractor is placed such that the open end faces the spinal canal/cord, allowing an unobstructed view of the neural compression. The patient is draped for a thoracotomy in case conversion to an open procedure is necessary.

TECHNIQUE FOR TRANSTHORACIC THORACOSCOPIC APPROACH

Anesthesia is induced with a double-lumen intubation. The patient is then repositioned in the lateral decubitus position. Anteroposterior (AP) and lateral fluoroscopy are used to mark the vertebral level and the anterior/posterior margins of the vertebral column on the lateral chest wall.¹⁸ The four portal incisions are then marked around the level of interest (Fig. 131.2). The working portal is centered at the level of the index vertebral body just posterior to the posterior axillary line.⁷ A portal for the endoscopic camera is marked two or three intercostal spaces directly above or below the working portal. The camera is placed superior to the working portal to view lower thoracic levels and inferior to the working portal to view upper levels.¹⁸ The two additional portals are used for suction/irrigation and retraction along the anterior axillary line.

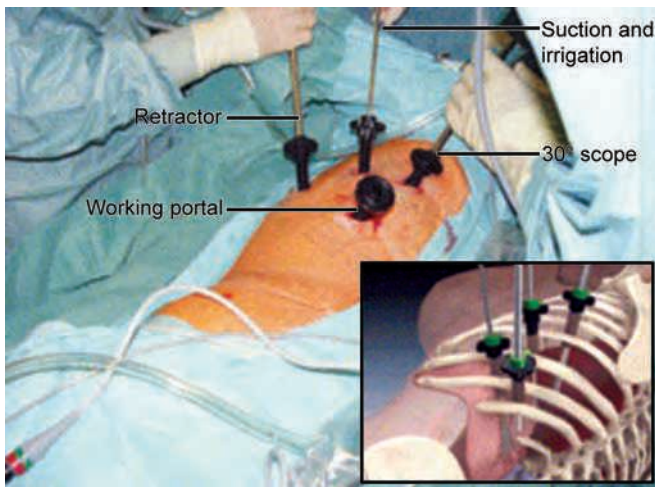


Fig. 131.2: Intraoperative photograph depicting thoracoscopic portal placement.

Source: Reprinted with permission from Beisse R, Trapp O. Thoracoscopic management of spinal trauma. *Oper Tech Neurosurg.* 2005;8(4):205-13, Elsevier.

Single-lung ventilation is initiated by the anesthesiologist. A 10 mm incision in line with the rib is made at the superior portal. The intercostal muscles are bluntly dissected until the rib is identified. A curved clamp is placed superior to the rib penetrating the pleural cavity. A finger is inserted into the chest to feel for any pleural adhesions. A cannula is placed into the chest followed by a 30° endoscope. The pleural space is examined for adhesions, deflation of the lung is confirmed, and the great and intercostal vessels are identified. The remaining three portals are placed under direct endoscopic visualization.¹⁸ A fan retractor is placed in the inferior portal to protect to the deflated lung and diaphragm.

The intrathoracic location of the disc space and vertebrae are identified under fluoroscopy. A harmonic scalpel is used to incise the overlying pleura. A flap is lifted exposing the lateral vertebral body and rib head. In cases at or below the thoracolumbar junction, the diaphragmatic insertion needs to be incised and lifted from the vertebral bodies.²⁷ The segmental artery is exposed, ligated with vascular clips, and coagulated with bipolar cautery. Ligation of the segmental artery is a crucial step when performing a corpectomy as uncontrolled bleeding may necessitate conversion to an open procedure.¹⁸ Some surgeons prefer placing K-wires or screws to use as fixed landmarks in the vertebral bodies above and below the level of the corpectomy.²⁷ The intervertebral discs are then excised with a rongeur and curette. The central portion of the vertebral

body is removed using a high-speed burr. The anterior and posterior vertebral body walls are initially preserved to protect the spinal canal. The proximal rib head is excised exposing the underlying pedicle. The pedicle is then resected in order to decompress the spine. The remaining posterior vertebral body is resected completing the decompression.

An expandable titanium cage is placed in the defect and expanded under fluoroscopic guidance. Posterior instrumentation via pedicle screws may also be performed through separate posterior incisions. The diaphragm is repaired endoscopically if needed. A chest tube is placed through the working portal. Reinflation of the lung is monitored under direct visualization. The remaining cannulas are removed and the portal incisions are closed in layers.²⁷

CONSIDERATIONS AND COMPLICATIONS OF THORACOSCOPY

Thoracoscopic surgery of the spine can be performed safely in the hands of an experienced surgeon. Advantages to this technique include a direct trajectory to the anterior thoracic spine, minimal tissue and rib retraction, decreased postoperative pain, and shorter hospitalizations.²⁸ The rate of approach-related complications has been reported as 1.3–5.7% in several large studies.^{27,29,30} Serious complications related to thoracoscopy exist including injury to the great vessels, postoperative diaphragmatic hernias, and splenic laceration.^{27,31} Manipulation of long endoscopic instruments while operating with two-dimensional visual cues may lead to a significant learning curve.

Pulmonary complications are often associated with thoracoscopy. Complications of single-lung ventilation and inadvertent lung injury are important to consider. Double-lumen intubation is more challenging for the anesthesiologist. Improper placement, inaccurate tube diameter, and incomplete obstruction of the operative lung can lead to air leaks into the deflated lung placing it at risk of injury. The duration of single-lung ventilation is typically longer for spine surgery than most thoracoscopic procedures. Prolonged periods of nonventilation may cause an accumulation of bronchial secretions in the deflated lung. If the secretions are not cleared properly they can lead to postoperative atelectasis and pneumonia. Therefore, an aggressive postoperative respiratory therapy regimen is essential.³² Iatrogenic atelectasis during thoracoscopy also leads to a ventilation-perfusion mismatch that may cause arterial desaturation, CO₂ retention, and respiratory acidosis.^{31,32}

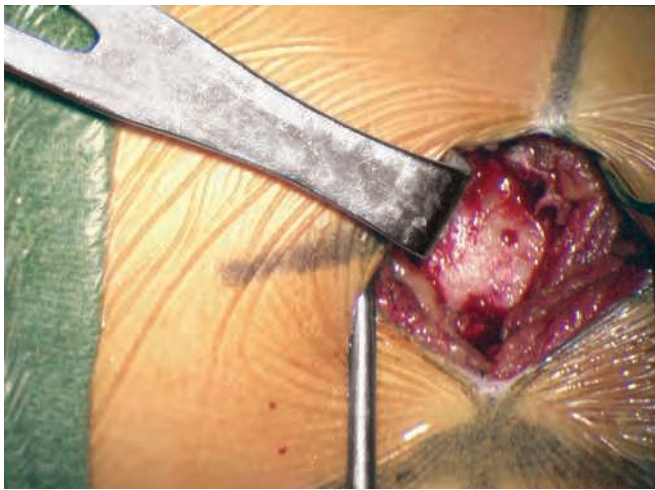


Fig. 131.3: Intraoperative photograph demonstrating exposure of the pleura. Approximately, 2 cm of the rib has been removed and the pleura is visible in the center of the wound.

Thoracoscopic instruments may also lead to complications. The trocars should be placed gently to avoid injury to the intercostal nerves and resultant intercostal neuralgia. Some surgeons recommend the use of soft trocars to reduce stress on the nerve, as they are manipulated during surgery.¹⁰ The proximity of the lung, large vessels, diaphragm, and organs immediately beneath the diaphragm requires caution when placing the trocars.²⁷ Injury to the lung parenchyma may lead to persistent air leaks.

TECHNIQUE FOR MINI-OPEN LATERAL RETROPLEURAL APPROACH

Anteroposterior (AP) and lateral views are obtained with fluoroscopy. The operative level is identified and the anterior and posterior margins of the vertebra are marked. A 3–4 cm incision is made at the midaxillary line directly over the index vertebra in the direction of the rib.¹¹ The rib is exposed subperiosteally, reflecting the neurovascular bundle inferiorly. A 2 cm segment of rib directly overlying the vertebra is removed and set aside for use as autograft (Fig. 131.3).^{8,26} At this point, the parietal pleura is exposed. The plane between the pleura and endothoracic fascia is developed with a sponge stick, peanut or with a fingertip.^{8,26} Once the lateral vertebral body is reached fluoroscopy is utilized to place a series of tubular dilators through the defect, sweeping the pleura, and lung anteriorly.²⁶ An expandable split-blade retractor is placed over the dilators and secured to the flexible table-mounted retractor arm (Fig. 131.4).

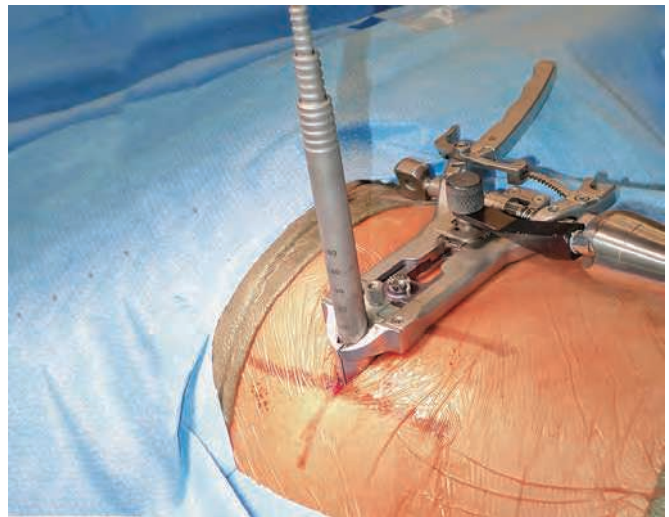


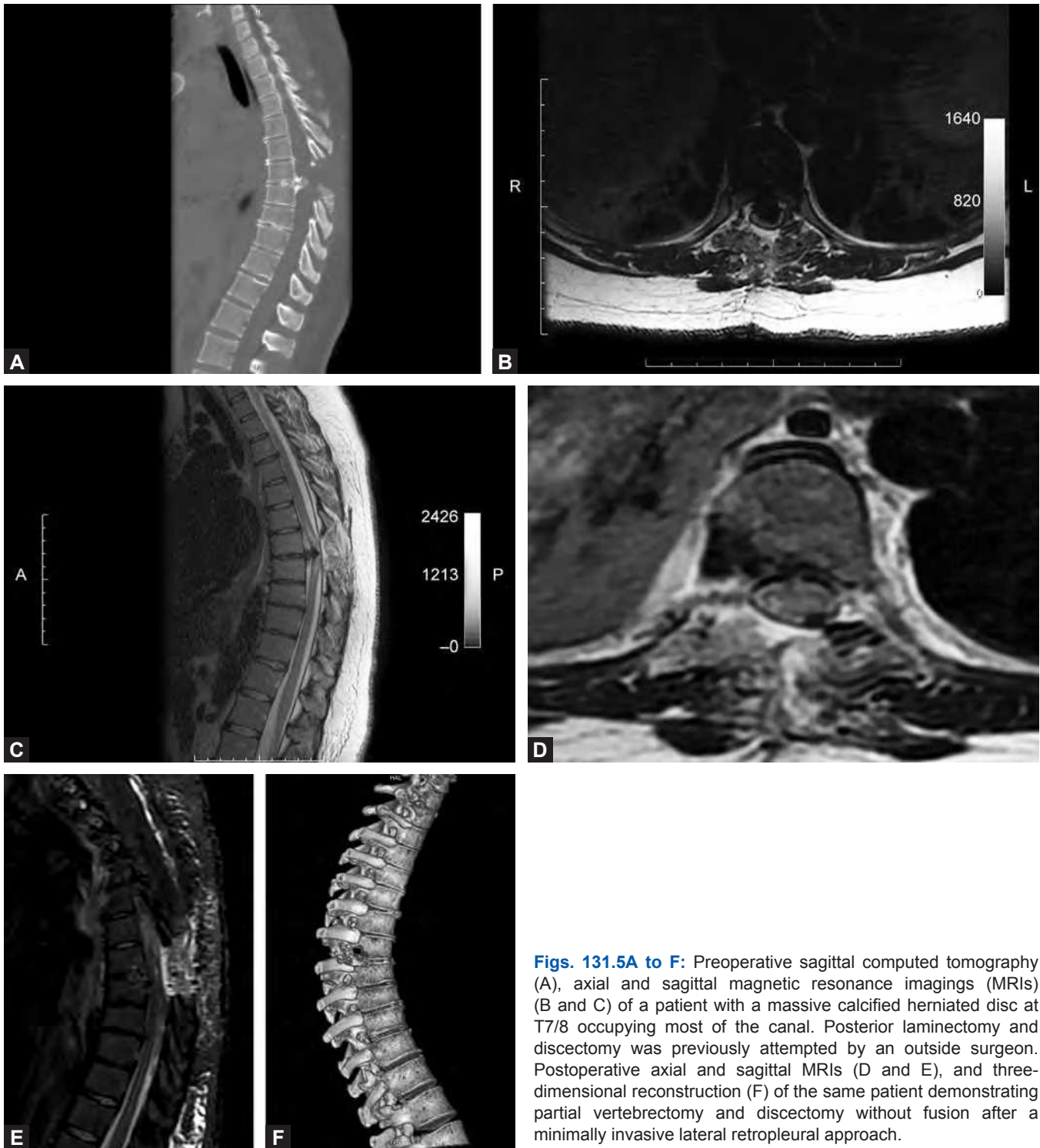
Fig. 131.4: Photograph of the tubular dilators and table-mounted retractor arm in place.

Discectomy

When performing a thoracic discectomy, a trough is created anterior to the canal by drilling the posterior third of the vertebral body adjacent to the disc space (Figs. 131.5A to F).⁷ A thin shell of the posterior vertebral body with the herniated disc is left in place protecting the dura. The shell and herniated disc are then removed by gently pulling anteriorly into the trough, thereby dissecting away from the dura and spinal cord. Large calcified herniated discs may be adhered to the posterior longitudinal ligament (PLL) and dura that may lead to inadvertent durotomy during the discectomy.^{6,11} Using a high-speed burr to create a cavity and to decrease the size of the calcified disc may decrease thoracic cord compression while obviating the need to detach the calcific disc from the adhered dura. Fusion is not necessary in most cases. However, if large portions of the vertebral bodies are removed, then the resected segment of the rib may be used as an autograft.⁷

Corpectomy and Fusion

The vertebra and intervertebral discs above and below are subperiosteally exposed (Fig. 131.6). The segmental artery is cauterized and resected as proximally as possible.^{8,26} The rib head at the corresponding vertebra and possibly caudal vertebra need to be identified and excised to fully expose the vertebral body, pedicle and adjacent intervertebral discs.²¹ The pedicle is removed using a high-speed burr and Kerrison rongeur to gain entrance into the canal,



Figs. 131.5A to F: Preoperative sagittal computed tomography (A), axial and sagittal magnetic resonance imaging (MRIs) (B and C) of a patient with a massive calcified herniated disc at T7/8 occupying most of the canal. Posterior laminectomy and discectomy was previously attempted by an outside surgeon. Postoperative axial and sagittal MRIs (D and E), and three-dimensional reconstruction (F) of the same patient demonstrating partial vertebrectomy and discectomy without fusion after a minimally invasive lateral retropleural approach.

exposing the lateral dura, and exiting nerve roots.^{8,21,22} A discectomy is then performed using angled curettes and a pituitary or Kerrison rongeur. The borders of the vertebral

body to be excised are clearly visible. The corpectomy is then carried out using a high-speed burr, rongeurs, and curettes until a thin portion of the anterior vertebra is

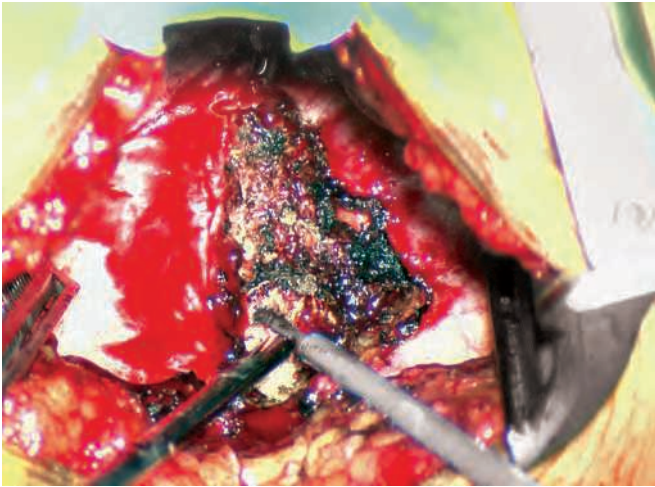


Fig. 131.6: The thoracic vertebral body to be resected is exposed subperiosteally.

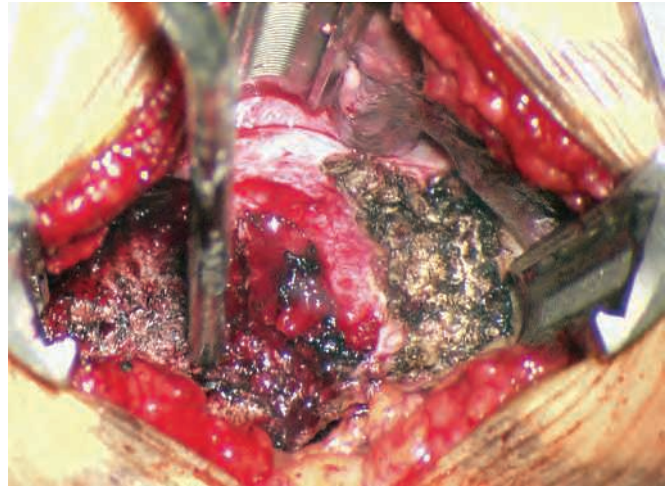


Fig. 131.7: Intraoperative photograph demonstrating a corpectomy. The lateral vertebral body has been resected and tumor is present within the corpectomy site. The anterior longitudinal ligament is intact at the top of the photograph.

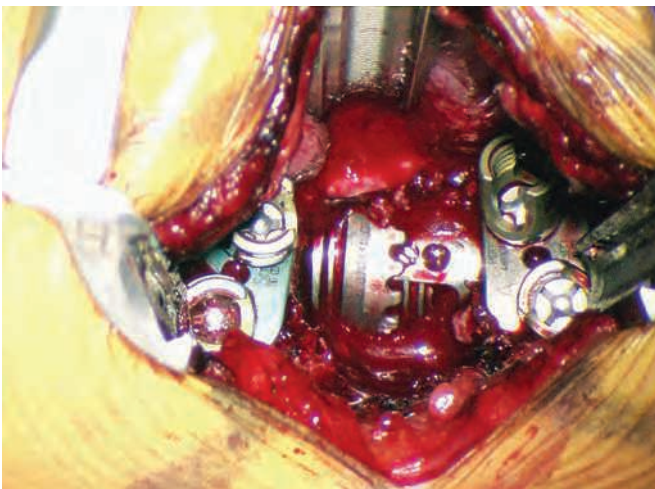


Fig. 131.8: The expandable titanium cage has been placed into the defect. Anterolateral plates are placed in the vertebral bodies above and below.

preserved with the anterior longitudinal ligament (ALL) (Fig. 131.7).²⁶ The PLL may be left intact if it is not involved in the compressive pathology.²¹

An expandable titanium cage is sized and inserted into the defect and expanded until appropriate sagittal alignment is attained.^{11,26} Anterolateral plating of the adjacent vertebrae and a connecting dual rod construct may be used to achieve fixation (Fig. 131.8).²⁶ A posterior percutaneous pedicle screw-rod complex may also be used to achieve fixation and is placed in either the lateral decubitus position or after the patient is repositioned prone on the Jackson table.^{9,33} The retractor is removed and the pleura is

evaluated for tears. Placement of a chest tube is not necessary, if the pleura is not violated.

CONSIDERATIONS AND COMPLICATIONS OF MINI-OPEN LATERAL RETROPLEURAL APPROACH

At the onset of the procedure, it is essential to obtain high-quality orthogonal fluoroscopic views when marking the vertebral borders as parallax may result in improper dilator placement.²⁶ Anterior displacement of the dilator may result in resection of the ALL or damage to the great vessels.

Bleeding from the segmental artery is sometimes encountered after cauterization. Ligation can be difficult through the minimal access portal; however, hemostatic agents, and pressure will usually achieve hemostasis.²⁶ It is important to resect the segmental artery prior to beginning the corpectomy, as bleeding can be brisk.²¹ Any remaining bleeding may then be controlled with bone wax or a gelatin sponge.¹¹

Overall complication rates related to the MIS lateral retropleural approach are reported from 12.5% to 15.4%.^{6,11,33,34} Pleural tears are the most common complication encountered through the MIS lateral retropleural approach. Pleural tears occurred in 11 of 38 (28.9%) patients in a series by Scheufler. Tears in eight patients were repaired primarily without a subsequent pneumothorax, while three patients

required placement of a chest tube.¹¹ The surgeon must be cognizant of this risk and be prepared to place a chest tube or red rubber catheter at the end of the procedure to treat the iatrogenic pneumothorax.²⁶ Patients with osteomyelitis or metastatic disease may have marked paraspinal pleural reactions with adhesive thickening that can distort the interfascial planes increasing the risk of pleural tears.⁸ Additional complications are similar to the open or endoscopic approaches and include infection, migration of the implant, dural tears, intercostal neuralgia, postoperative atelectasis, pneumothorax, or pleural effusions.

OUTCOMES

In recent years, there have been numerous articles evaluating the utility of a mini-open and thoracoscopic approach to the thoracic spine. Early cohorts are promising for the minimally invasive techniques in the setting of trauma, infection, neoplasm, and disc herniations.^{6,8,11,27,29,30,33-39} Khoo et al. reported results of 371 patients who underwent thoracoscopic corpectomy and fusion for thoracolumbar fractures.³⁰ The authors demonstrated a significant learning curve for the thoracoscopic technique; average operative time initially was 300 minutes but later decreased to 180 minutes with experience.

Quint et al. reported outcomes of 167 patients who underwent thoracoscopic single-level discectomy without fusion and found good to excellent outcomes in approximately 80% of patients in regards to pain and motor function.³⁵ The complication rate in this cohort was 15.6% with three patients (1.8%) requiring reoperation due to severe pain from segmental instability after the discectomy. The authors also demonstrated complete decompression on postoperative computed tomography in 98% of patients.

The MIS lateral retropleural approach for thoracic discectomy and corpectomy is gaining popularity (Table 131.1).^{6,11,33,34,36,37} Smith et al. reported a series of 52 patients treated with corpectomy and fusion for thoracolumbar burst fractures.³³ Of the patients presenting with acute neurologic deficit after trauma, 94.2% demonstrated trends toward significant improvement in the ASIA (American Spinal Injury Association) classification at 1 year follow-up. Sheufler's series of 38 patients demonstrated successful fusion at 1 year in 8 of 10 (80%) patients treated for infection or fracture, but only 14 of 28 (50%) of patients treated for metastatic neoplasm.¹¹ Both studies found a significant reduction in operative time, decreased

blood loss, and shorter hospitalizations using the MIS approach when compared to an open procedure.^{11,33}

There are several studies reporting on the outcomes of MIS lateral retropleural discectomy for symptomatic thoracic disc herniations (TDH).^{6,36,37} Uribe et al. compared their results to a review of the literature on reported open surgeries and found a trend toward shorter operative times (182 versus 229.3 minutes), reduced blood loss (290 vs 562.9 mL), and fewer hospitalization days (5.0 vs 8.6 days) in their MIS group.⁶ The rate of complications was also significantly lower in the MIS group compared to the open group (15% vs 36.7%). Kasliwal et al. reported on seven patients after a mini-open discectomy for symptomatic TDH and found myelopathy improved in three out of seven patients and radicular pain improved in four out of four patients.³⁷ Moran et al. reported results of MIS lateral retropleural discectomy without fusion in 17 patients with large calcified TDH and myelopathy.³⁶ Outcomes demonstrated improvement on the Frankel Grading system in 76% of patients at 2-year follow-up. The Oswestry Disability Index (ODI) also improved from 38% to 21% at 2-year follow-up. In this study, there was no postoperative kyphosis or evidence of collapse in any patient treated with single-level discectomy alone without fusion.

CONCLUSION

The potential for the minimally invasive techniques for thoracic spine surgery to improve postsurgical outcomes is promising. Both the transthoracic thoracoscopic and minimally invasive lateral retropleural approaches allow excellent visualization of the anterior thoracic vertebrae. Corpectomies and discectomies performed through traditional open approaches are associated with significant morbidity and increased rates of complications. Thoracoscopic approaches have minimized the morbidity of open approaches but still require intrapleural access with single-lung ventilation and chest tube placement. The MIS lateral retropleural approach obviates the need for a chest tube, but pleural tears are common and must be addressed when they occur. There is a steep learning curve with both MIS and thoracoscopic techniques and the surgeon must be familiar with the applied anatomy, special equipment, and unique complications associated with each approach. Minimally invasive thoracic spine surgery offers the benefits of direct access to the anterior column for conventional discectomy and corpectomy while minimizing incisional trauma and tissue dissection.

Table 131.1: Reported outcomes and complications from clinical studies on MIS lateral retropleural approach.

<i>Authors (Year)</i>	<i>Number of patients</i>	<i>Indications</i>	<i>Procedure</i>	<i>Outcomes measured</i>	<i>Results</i>	<i>Complications</i>
Scheufler ¹¹	38	Tumor, <i>n</i> = 28 Infection, <i>n</i> = 5 Trauma, <i>n</i> = 5	Discectomy, corpectomy and fusion	ORT, EBL, LOS, VAS, sagittal correction, fusion rate	ORT = 163 min, EBL = 280 mL, LOS = 7.4 days, VAS = 2.7 ± 0.9 Sagittal correction = 19.3°, fusion = 50% (tumor) 80% (infection, trauma)	Pleural tear, <i>n</i> = 11 atelectasis/pleural effusion, <i>n</i> = 3 dural tear, <i>n</i> = 1 hardware failure, <i>n</i> = 1
Smith et al. ^{33*}	52	Trauma	Discectomy, corpectomy, and fusion	ORT, EBL, LOS, ASIA grade	ORT = 127.5 minutes, EBL = 300 mL, LOS = 4.0 days, ASIA class improved 73%	Overall 15.4%
Uribe et al. ⁸	4	Tumor, <i>n</i> = 2 Trauma, <i>n</i> = 2	Excision of neurofibroma (<i>n</i> = 1), discectomy, corpectomy and fusion (<i>n</i> = 3)	ORT, EBL	ORT = 5 hours EBL = 460 mL	Pleural tear, <i>n</i> = 1
Kasliwal et al. ³⁷	7	TDH	Discectomy	EBL, LOS, Nurick scale, VAS	EBL = 180 mL, LOS = 2.6 days, Nurick score improved in three patients, VAS improved 7.2 > 3.1	None
Moran et al. ³⁶	17	TDH	Discectomy	Frankel grade, ODI	Frankel grade = 76% improved 1 to 2 grades, ODI = 38% > 21%	Pleural tear, <i>n</i> = 5 Intrapleural CSF leak, <i>n</i> = 1 Pulmonary embolism, <i>n</i> = 1 Pneumonia, <i>n</i> = 1
Baaj et al. ^{34*}	80	Tumor, <i>n</i> = 21 Infection, <i>n</i> = 2 Trauma, <i>n</i> = 57	Discectomy, corpectomy, and fusion	Complications	–	Overall 12.5% Dural tear, <i>n</i> = 2 Intercostal neuralgia, <i>n</i> = 2 DVT, <i>n</i> = 2 Pleural effusion, <i>n</i> = 1 Hardware failure, <i>n</i> = 1 Wound infection, <i>n</i> = 1 Hemothorax, <i>n</i> = 1
Uribe et al. ⁶	Total = 60 Retropleural, <i>n</i> = 15 Transpleural, <i>n</i> = 45	TDH	Discectomy and fusion	ORT, EBL, LOS, VAS	ORT = 182 minutes, EBL = 290 mL, LOS = 5 days, VAS = 7.8 > 3.1	Overall 15% Dural tear, <i>n</i> = 7 Intercostal neuralgia, <i>n</i> = 1 Urinary retention, <i>n</i> = 1 Atelectasis, <i>n</i> = 1 Pleural effusion, <i>n</i> = 1 Pneumonia, <i>n</i> = 1 Extrapleural air, <i>n</i> = 1 New-onset weakness, <i>n</i> = 1 Hardware infection, <i>n</i> = 1

(ORT: Operative time; EBL: Estimated blood loss; LOS: Length of hospital stay; VAS: Visual analog scale; ASIA: American Spinal Injury Association; TDH: Thoracic disc herniation; ODI: Oswestry Disability Index; CSF: Cerebrospinal fluid; DVT: Deep vein thrombosis).

*Baaj et al.³⁴ reported on complications in a cohort of patients that overlaps with patients reported by Smith et al.³³

KEY POINTS

- Minimally invasive surgery of the thoracic spine is a developing field indicated for the treatment of fractures, infections, neoplasm, and disc herniations causing cord compression.
- Discectomy with or without fusion and corpectomies with anterior reconstruction can be successfully performed with minimal approach-related trauma to the surrounding tissues.
- Both the thoracoscopic transthoracic and minimally invasive lateral retropleural techniques have demonstrated comparable clinical outcomes when compared to traditional open approaches.
- Benefits of minimally invasive spine surgery include decreased blood loss, postoperative pain, hospitalizations and complications.
- There is a steep learning curve that the surgeon must overcome in order to fully appreciate the benefits of the minimally invasive techniques.

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Minimally Invasive Lumbar Surgery for Disc Herniations and Stenosis

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Snapshot

» Evolution of Minimally Invasive Spine Surgery

» Tubular Retractor-Assisted Minimally Invasive Spine Surgery

INTRODUCTION

The pathophysiology and natural history of degenerative disc disease was first explored by Kirkaldy-Willis in the 1970s through a study of autopsy specimens of the human spine.^{1,2} Disc dysfunction and herniation were proposed to be the initial events in the degenerative cascade, with the end result being spinal canal stenosis.

Disc herniation is the posterior protrusion, or in severe cases, extrusion of the nucleus pulposus through a tear in the annulus fibrosus often leads to irritation and compression of nerve roots. This is usually manifested by pain and/or weakness in the area of distribution of the affected nerve(s). The pain in the lower limbs is often sharp and shooting in nature and in some instances can be crippling, adversely affecting the patient's normal daily activities and leading to functional decline. Initial treatment options include pain medication, anti-inflammatory agents, physical therapy, and in some cases, epidural corticosteroid injections. When conservative treatment methods fail, open surgery is considered. Surgical options include laminectomy with discectomy, laminotomy with discectomy, and microsurgical discectomy (MSD). However, open surgical procedures are associated with many drawbacks—notably soft tissue injury from the large skin incision and subcutaneous dissection, stripping of paraspinal muscle attachments, as well as trauma to the muscles from the retraction required for adequate visualization.^{3,4} In addition, the need for cauterization of blood vessels over a large area

of exposure may further hinder the blood supply and healing of the paraspinal muscles.

Degenerative lumbar spinal stenosis is one of the leading indications for spinal surgery in the elderly. This disease results from compression of the dural sac and nerve roots secondary to a summation of degenerative changes such as intervertebral disc bulging or herniation, ligamentum flavum buckling, facet joint hypertrophy, and osteophyte formation. Affected patients have diminished standing and walking tolerance, mostly attributable to a reduction in the spinal canal diameter and cross-sectional area. Clinical symptoms include a claudication type pain in the lower back and legs and sometimes associated motor and sensory deficits.⁵ These symptoms are more pronounced in extension, and activities that involve spinal flexion, such as sitting, walking uphill or leaning forward on a shopping cart, can often partially alleviate symptoms.⁵⁻⁷

Traditional open surgery performed to relieve lumbar stenosis involves an open bilateral laminectomy to achieve a wide decompression. This is typically accompanied by decompression of the medial portion of the facet joints, including the lateral recesses, to free the neural elements.⁸ Open approaches such as these are well established for relieving the symptoms of nerve compression. However, there are potential risks and complications such as blood loss, postoperative pain, and iatrogenic spinal instability. For elderly patients, these factors can be particularly concerning due to comorbidities and a lower cardiopulmonary reserve.^{9,10} Also, postoperative analgesia must be used carefully in the elderly due to reduced hepatorenal function.

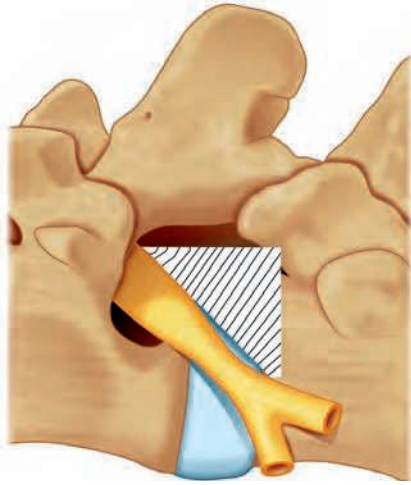


Fig. 132.1: An illustration depicting Kambin's triangle used for posterolateral transforaminal approaches to the disc space.

All of the afore-mentioned concerns with open surgery have driven a need for less invasive exposures. Minimally invasive spine surgery (MISS), consisting of techniques utilizing special instruments that enable surgeons to operate through smaller incisions and focused surgical corridors, has emerged as a rapidly expanding field in spine surgery.

EVOLUTION OF MINIMALLY INVASIVE SPINE SURGERY

The concept of MISS originated from early experiments with chymopapain by Smith et al. in 1963.¹¹ These authors were the first to inject chymopapain into the nucleus pulposus of intervertebral discs in patients with sciatica to achieve chemonucleolysis (disc dissolution). Later in 1975 Hijikata et al.^{12,13} and in 1983 Kambin and Gellman¹⁴ independently described percutaneous discectomies via a posterolateral approach to the spine. They utilized an approach through a neurological “safe zone” overlying the dorsolateral aspect of the disc, now known as Kambin's triangle (Fig. 132.1). This triangle consists of an area between the right angle formed by the superior endplate of the caudal vertebral body and the dura/traversing nerve root, with the exiting nerve root forming the hypotenuse.¹⁵ These procedures were initially performed by passing a cannula under fluoroscopic control into the intervertebral disc (through Kambin's triangle) and using nucleotomes and long pituitary rongeurs to remove the disc fragments percutaneously. With technological advancements in fiber-

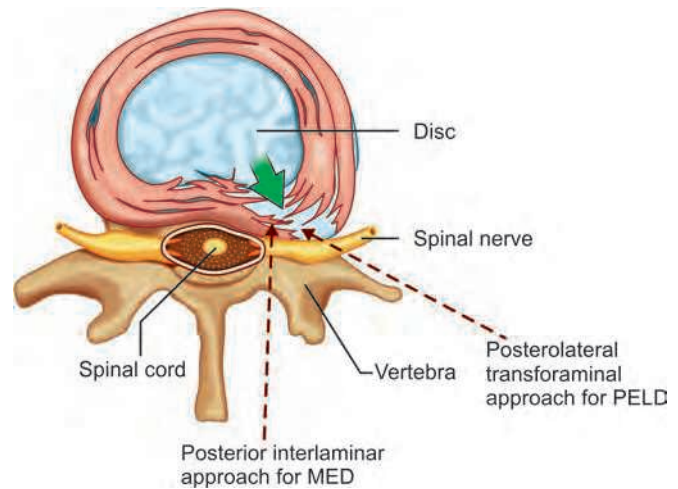


Fig. 132.2: The posterior interlaminar approach to the spine compared to the posterolateral transforaminal approach. [(PELD: Posterolateral endoscopic lumbar disectomy; MED: Microendoscopic discectomy)]

optics and video imaging, newer sophisticated endoscopes were developed. In 1997, Yeung¹⁶ introduced the first working channel endoscopic system for commercial distribution, known as Yeung Endoscopic Spine Surgery (Richard Wolf Surgical Instruments, Vernon Hills, IL, USA). Minimally invasive spine surgery using this endoscopic posterolateral transforaminal approach to the intervertebral disc has come to be known as PELD (posterolateral endoscopic lumbar disectomy).

Following the trend of smaller incisions, in 1997, Foley and Smith¹⁷ developed a novel minimally invasive posterior paramedian approach to the spinal canal for disc disease, similar to that used in open MSD. In contrast to the micro-lumbar procedure, access to the interlaminar space was achieved through serial dilation over a guidewire using sequentially sized cannulas, and finally a tubular retractor, to expose the operative window. An endoscope passed through the retractor was utilized to visualize the surgical field.¹⁸ This MISS technique digressed from the above-mentioned posterolateral approach and is often referred to as microendoscopic discectomy (MED). Here, a posterior interlaminar approach was employed to access the spinal canal and disc (Fig. 132.2). Subsequent refinements to the technique and development of better instrumentation led to the second-generation MED system in 1999, called METRx (Medtronic Sofamor Danek Inc, Memphis, TN, USA). The second-generation systems provided improved three-dimensional visualization using an operative microscope. Another popular MED system is the Destandau Endospine system (Karl STORZ GmbH & Co KG, Tuttlin-

gen, Baden-Württemberg, Germany) which incorporates a cone shaped, free-hand working channel type of assembly.^{19,20}

Anterior laparoscopic and retroperitoneal endoscopic approaches²¹⁻²³ to the spine, as well as lateral transpsoas approaches,^{24,25} have also been developed and are used for lumbar interbody fusion procedures. However, description of these approaches and their applications to MISS is beyond the scope of this chapter.

Given the diverse nature of approaches, techniques and instrumentation systems developed to advance the practice of MISS, there is a consistent underlying philosophy: preservation of the structural integrity and function of the lumbar paraspinal muscles as much as possible. A brief description of the anatomy of the paraspinal muscles and their function is essential to understand this rationale.

Lumbar Paraspinal Musculature and the MISS Rationale

The erector spinae group that comprises the intrinsic musculature of the lumbar spine consists of the multifidus, longissimus and iliocostalis muscle subsets. Due to their medial location and unique architectural anatomy, the multifidus group contributes to important biomechanical characteristics of the spine. The multifidi are believed to be the major posterior spinal stabilizing muscles due to comparatively larger physiological cross-sectional area and shorter fiber length, enabling them to generate greater forces over relatively short distances.^{26,27} Biomechanical studies have demonstrated that the multifidus opposes the counter-rotation force generated by the abdominal musculature on the lumbar vertebrae. Thus these muscles play a vital role in maintaining truncal stability in concert with the abdominal muscles.²⁸ However, multifidi are also the muscles that suffer most of the injury during dissection and retraction in open posterior lumbar surgeries.

The multifidus also has a unique nerve supply without any additional intersegmental collaterals, in contrast to the other lumbar paraspinal muscle groups. This unisegmental innervation is derived from the medial branches of the dorsal rami, which at each level, course through a groove between the mammillary and accessory processes. Here, these nerves branch and become relatively fixed by the fibro-osseous mamilloaccessory ligament. This predisposes them to injury with wide midline dissection and retraction during open posterior approaches.^{29,30} To address this issue, a paramedian approach along the interfascial plane between the multifidus and the longissimus muscles, like that described by Wiltse et al.,³¹ is employed in posterior

MIS surgery. This limited dissection is reported to result in better preservation of the vascularity of the paraspinal muscles and reduced postoperative ischemic necrosis and scarring. Apart from minimizing soft tissue and paraspinal muscle injury, MISS techniques aim to preserve the osseoligamentous posterior elements as much as possible. Conventional open surgical approaches resect the lamina and spinous processes to gain access to the spinal canal and the disc space. This leads to detachment of the multifidus and the supraspinous/infraspinous ligaments. With the use of MISS techniques and by limiting bony resection to laminotomies, spinal motion segment stability can be maintained by preserving these soft tissues and osseoligamentous structures.

Intraoperative retractor-induced injury to the paraspinal muscles has been studied by numerous investigators.³²⁻⁴² Intramuscular pressures as high as 158 mm Hg have been reported in the erector spinae group intraoperatively while using various self-retaining retractors.⁴² These retractors exert constant point pressure on the tissues to stay anchored in position. This nonuniform pressure, applied mostly at the edges of the exposed incision and the underlying paraspinal muscles, leads to impediment of local blood flow and subsequent ischemic muscle necrosis. In contrast, tubular retractor systems developed for the MED MISS procedures have been shown to exert significantly lower pressure on the surrounding paraspinal muscles. This could be attributed to the uniform cylindrical geometry that minimizes the pressure per unit area while maximizing the surface area of contact. The intramuscular pressures in the vicinity of tubular retractors decreases quickly after removal of the initial expanders, whereas open retractor continue to exert high pressures on the surrounding muscle when deployed.⁴¹ In addition to maintaining uniform pressure on the surrounding tissue throughout the procedure, tubular retractors can be mounted to the operative table with special assemblies.⁴³

Thus, the technique of MISS has been developed with the above-mentioned anatomical and biomechanical considerations and instrumentation design factors. In addition to tubular retractors, some of the technological discoveries that have contributed to MISS include innovations in spinal imaging techniques, fiberoptic lighting and image recording technologies, and operative microscopes and endoscopes with working channels.⁶

The tubular retractor-assisted microendoscopic MISS, which was initially devised and used for lumbar discectomies, has found increasing applications in recent years. Some of these include decompression for lumbar canal



Fig. 132.3: A serial dilator assembly used to bluntly separate the paraspinal muscle fibers.

stenosis, minimally invasive instrumented lumbar fusion procedures such as PLIF (posterior lumbar interbody fusion) and TLIF (transforaminal lumbar interbody fusion), and intra and extradural spine tumor resection procedures.⁴⁴

TUBULAR RETRACTOR-ASSISTED MINIMALLY INVASIVE SPINE SURGERY

Surgical Approach

With the patient prone on the operating room table, the hips are placed in flexion to decrease lumbar lordosis and to allow expansion of the interlaminar spaces that increases the working area for tubular retractor placement. The incision site is identified about 15 mm from midline on the side of the pathology, and C-arm fluoroscopy is used to confirm position over the correct disc space. A 15–20 mm incision is made longitudinally through the skin and subcutaneous tissue, and the lumbodorsal fascia is incised. A guidewire or pin is advanced through the incision to reach the base of the superior lamina at the junction of the facet joint. The position of the wire is confirmed again in both anteroposterior and lateral fluoroscopic views. Serial dilators of sequentially incremental diameters are then threaded over the guidewire. This ensures that the paraspinal muscles fibers are separated gradually and bluntly rather than being cut (Fig. 132.3). This technique allows for minimal stripping of the muscles from their attachment sites and helps preserve the vascularity and innervation.



Fig. 132.4: An intraoperative fluoroscopic view confirming proper retractor placement.

The tubular retractor is then advanced over the final dilator, down to the lamina, ensuring that soft tissues and muscles do not get pinched in between. The position is again confirmed fluoroscopically (Fig. 132.4). The retractor is then connected to the flexible arm assembly mounted to the operating table to maintain position and prevent migration (Fig. 132.5). An endoscope or an operating microscope can be used through the tubular retractor and the procedure is performed using modified long-handled instruments such as rongeurs, disc forceps, curettes, and retractors (Figs. 132.6 and 132.7).

The tubular retractor system offers direct visualization of the operative field. However, the relatively limited field of view requires a high degree of anatomical familiarity and 360° degree orientation. To access adjacent spinal levels through the same skin incision, a wand maneuver can be performed (Fig. 132.8). This is accomplished by releasing the holder that mounts the tubular retractor to the operating table and introducing a wider dilator. The dilator can be used as a handle to reposition the retractor to an adjacent interlaminar space. The retractor is then secured again to its table mounted assembly.⁴⁵ The retractor can similarly be angled across midline, enabling the surgeon to reach a contralateral disc herniation. However, performing MISS through one small incision using a single retractor poses technical difficulties in approaching more than two adjacent segments. This limits the utility of tubular retractor-assisted MISS to procedures performed over

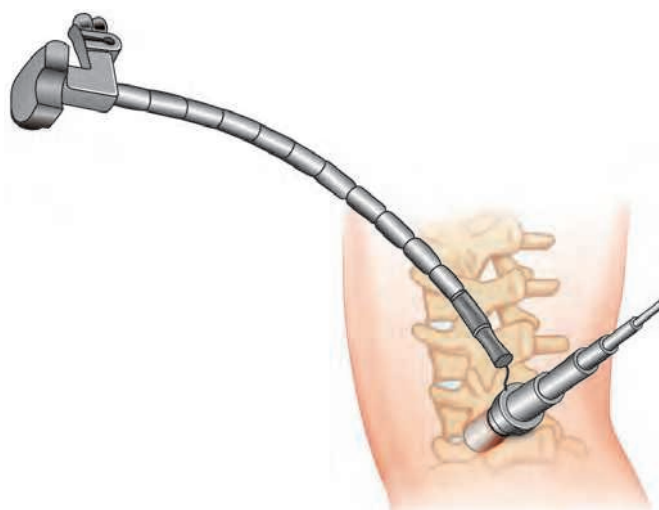


Fig. 132.5: A table-mounted flexible arm assembly connected to a cannula to maintain the retractor position intraoperatively.

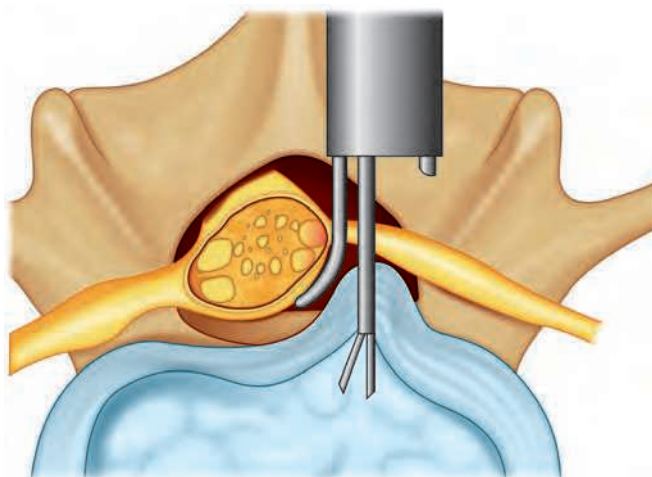


Fig. 132.6: Instruments inserted through a cannula to perform a discectomy.

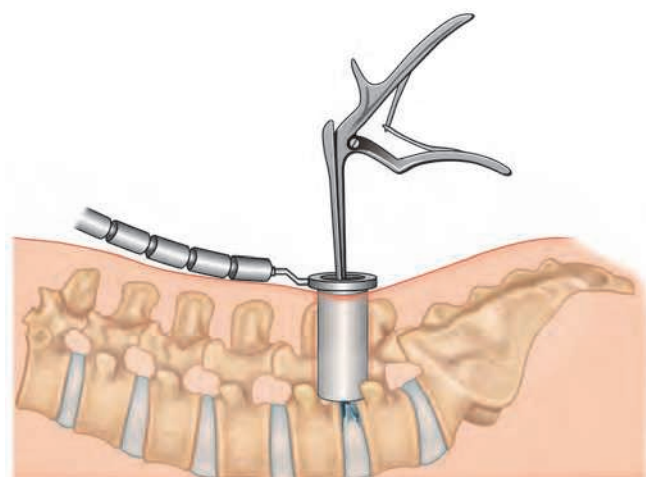


Fig. 132.7: A modified Kerrison rongeur passed through a retractor to remove soft tissue and bone piecemeal.

relatively short segments of the spine. After the surgery has been completed, the tubular retractor is removed and the muscles close upon each other in the potential space that the retractor previously occupied, thus limiting muscle damage compared to open surgery.

Lumbar Discectomy Using Tubular Retractors

Once the lamina has been reached by the technique mentioned above, removal of the overlying soft tissues is done through the tubular retractors with small rongeurs.

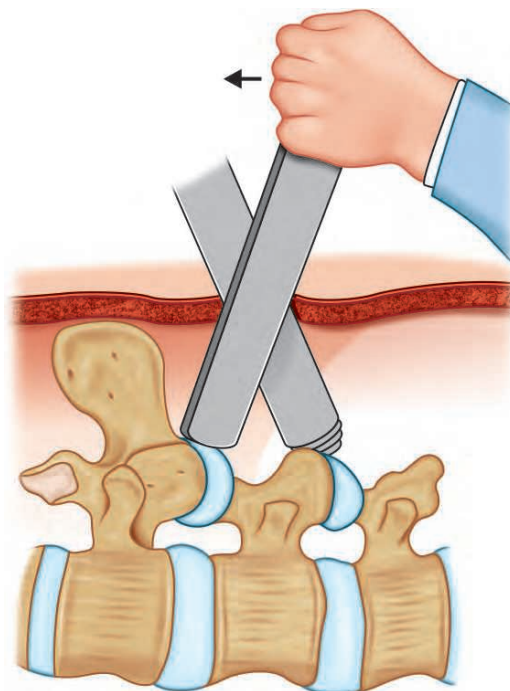


Fig. 132.8: The wandering maneuver enables the surgeon to modify the tubular retractor position in order to operate on adjacent spinal segments through one incision.

Adequate hemostasis is achieved with bipolar cautery forceps. The inferior edge of the superior lamina is identified and a laminotomy is performed, as well as a medial facetectomy in some cases. Bony resection is kept to a minimum while still providing adequate access to the disc

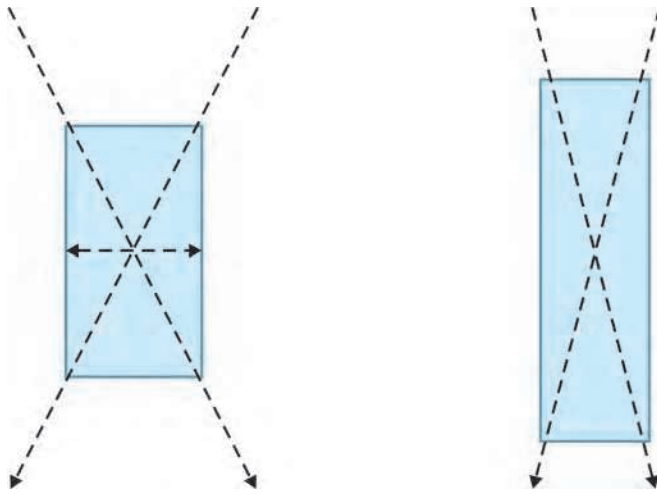


Fig. 132.9: An illustration depicting the effect of tube diameter and length on the degree of angulation that can be achieved by operative instruments passed through a tubular channel.

and the lateral recess. The ligamentum flavum is incised using special scissors and removed using modified rongeurs. The nerve root on the side of herniation is identified and exposed with gentle epidural dissection. After the nerve has been mobilized it can be retracted medially or laterally to access the prolapsed intervertebral disc. This is followed by discectomy using modified disc forceps, similar to an open microdiscectomy. Mobility and tension on the nerve root are reassessed and meticulous hemostasis is achieved before closure. The importance of hemostasis cannot be understated in minimally invasive procedures, as any significant residual bleeding after closure may lead to hematoma formation and compression of the neural elements. This problem is exaggerated by the relative lack of potential space for the hematoma to expand compared to traditional open exposures.

In general, a retractor with a tube diameter of 20 mm and a length of 40–50 mm is used for lumbar spine discectomy and decompression.⁴⁴ Utilizing the appropriately sized retractor is paramount as the surgeon might face technical difficulties introducing surgical instruments through a cannula that is too small in diameter or too long in length. Longer length tubes may be advantageous in obese patients, where there is a greater depth from the skin surface to the lamina. However, the length restricts the achievable degree of instrument angulation.⁴⁵ A shorter, large bore cannula provides a larger working area and permits a greater degree of angulation and mobility of instruments (Fig. 132.9). However, larger diameter tubes require increased soft tissue dissection and paraspinal muscle

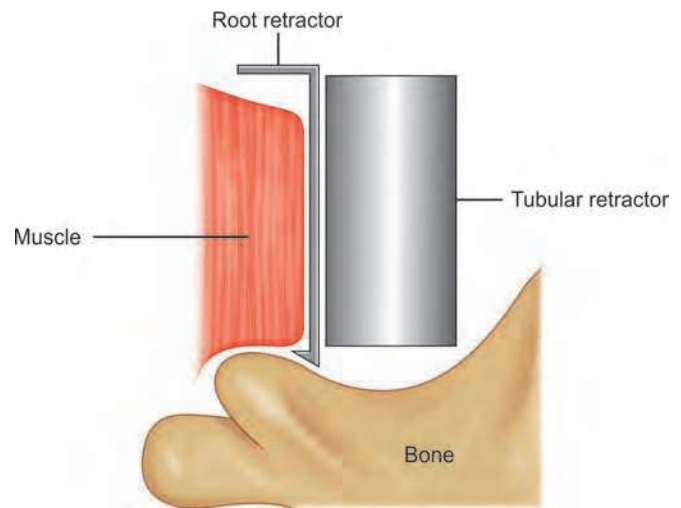


Fig. 132.10: A root retractor passed outside a cannula to prevent muscle from creeping in the distal lumen of the retractor tube.

splitting. In addition, docking the wider object into the interlaminar space may be technically difficult. Larger diameter tubes may also facilitate increased muscle creep into the lumen of the tube's distal opening, thereby reducing visibility. Using a root retractor placed flush outside the tube can prevent the surrounding muscles from sliding inside, through the tip (Fig. 132.10).⁴⁴

Due to the limited operative window, it is critical that the size and location of the disc herniation be carefully assessed prior to surgical intervention. In many instances, with thorough planning and good surgical skills, one incision may be all that is required to access the spinal canal, the lateral recess, and the foraminal space for far lateral disc removal.⁴⁶

Decompression of Lumbar Spinal Stenosis

Minimally invasive spine surgery for lumbar spinal stenosis using tubular retractors was first reported in a series of patients by Khoo and Fessler in 2002.⁴⁷ The technique was termed microendoscopic decompressive laminotomy. This procedure differs slightly from the one described for MED in that the incision and approach are slightly farther from midline. This allows greater angulation of the tubular retractor, permitting access to the central and contralateral spinal canal for decompression. Angled curettes and Kerrison rongeurs are required to extend the decompression to the contralateral lateral recess and foramen. The extent of resection of the ligamentum flavum is also greater than

that performed in a MED. Bony resection of the undersurface of the contralateral lamina using specialized burrs and curettes is done to create more space in the spinal canal. Cases of adjacent multilevel stenosis addressed through a single incision have been reported.⁴⁷ Once adequate canal decompression is achieved, annulotomy and standard discectomy can be done if indicated. Hemostasis is obtained prior to closure to avoid serious complications such as epidural hematomas.

Complications

Dural tears and nerve root injuries are the most frequently occurring complications with tubular retractor-assisted MISS.^{48,49} In a systematic review evaluating complications of tubular lumbar decompression and fusion procedures, Fourny et al.⁴⁹ reported that the rates of dural tears and nerve root injuries from some studies were higher in the minimal access group compared to the open surgical group; however, overall the complication rates were similar between groups. Poor depth perception with endoscopic surgery has been postulated as one of the factors behind the higher incidence of these complications.⁵⁰ The steep learning curve for the procedure also likely contributes to higher rates of technique-related complications.⁵¹ Other infrequently reported complications include wound hematomas, seroma formation, and wrong level surgery.^{48,52} Wound hematomas can lead to serious neurological complications due to the finite space with no place to expand. This situation can be avoided by obtaining hemostasis before closure, and placing surgical drains if there are any doubts about the adequacy of hemostasis.

Recurrent herniations have also been reported to occur more frequently with microendoscopic discectomy compared to open procedures.⁵⁰ The restricted working area offered by the tubular retractors could affect the identification and thorough removal of free fragments within the intervertebral space, leading to recurrence.

Procedural Considerations

Advocates of the open discectomy and decompression procedures have consistently cited the increased radiation exposure and steep learning curve as drawbacks to the MISS techniques. In a recent prospective controlled trial, Mariscalco et al.⁵³ studied the radiation exposure to the surgeon during open and minimally invasive microdiscectomies using tubular retractors. They concluded that the radiation exposure in MISS procedures was significantly

higher, with exposure levels approximately 10–20 times greater than in open procedures. However, with the use of protective lead aprons and thyroid shields, they found that approximately 1,623 MISS procedures could be performed per year before exceeding the permissible whole body radiation occupational exposure limits. Thus, despite the heightened radiation exposure levels, MISS MED appears to be a relatively safe procedure if appropriate protective equipment is worn. To further reduce radiation exposure levels, measures such as the “hands off” technique (removing one’s hands from the operative field and the vicinity of the radiation beam) during fluoroscopy and standing on the side opposite the fluoroscopy source are recommended.⁵³ The use of emerging technologies, such as navigation assisted fluoroscopy, have the potential to further reduce radiation exposure to both the surgeon and the patient.⁵⁴

Some authors have reported on the steep learning curve involved in transitioning from open to minimally invasive approaches.^{51,55} At present, there is scarce literature describing methods to improve learning efficiency and reduce the initial technique-related complications. Most surgeons would agree that with increased experience with minimally invasive techniques factors such as surgical times, blood loss, and complication rates are reduced as compared to those performed during the initial learning phase.^{51,55}

These issues can be taken in stride if the benefits of minimally invasive techniques truly outweigh the risks and translate into better clinical outcomes for patients. However whether these techniques significantly impact patient-related outcomes is still a matter of debate.

Patient Selection

In addition to the steep learning curve with MISS techniques there are a number of factors to consider in order to achieve optimal results.

Obesity

Minimally invasive spine surgery procedures are hypothesized to be advantageous in obese patients due to limited subcutaneous dissection and accelerated postoperative wound healing. However, excessively obese patients pose certain technical challenges. The distance from the skin to the intervertebral disc is greater which necessitates the use of longer instruments. A longer tubular retractor limits the degree of instrument angulation (*see* Fig. 132.9). This may

limit surgical access to the far reaches of the operative field and require excessive maneuvering of the retractor intraoperatively. Preoperative imaging studies must be analyzed in detail with obese patients to anticipate the length of the tubular retractor assembly required to perform adequate disc removal and decompression. In cases where this is unlikely to be fulfilled through MISS, open procedures should be considered.

Revision Surgery

Scar tissue from previous spinal surgery greatly increases the difficulty of reoperation. Wider surgical exposures are preferred for optimal appreciation of anatomy before approaching the scarred area overlying the dural sac. Complications such as dural tears occur more frequently during revision spine surgery.⁵⁶ In the event of a dural tear, open approaches offer distinct advantages in achieving effective repair compared to MISS. The surgeon should also be prepared to convert to open in cases where the technical difficulties and risks of complications outweigh the potential benefits of MISS. Considerable experience is required on the part of the surgeon to perform minimally invasive revision surgery safely and effectively in these complex cases.

Levels of the Involved Spinal Pathology

Smaller, localized spine pathology such as single-level disc herniation or canal stenosis is ideal surgical candidates for minimally invasive tubular surgery. The greater the number of spinal levels involved, the more difficult it becomes to adhere to minimally invasive practices. Multi-level herniations and extensive canal stenosis requiring bilateral decompression are more suited for open surgery. Additional steps, such as fusion and instrumentation, are often required in cases where adequate decompression may lead to spinal segmental instability. The complexity of surgery increases with the number of spinal levels involved.

Patient Education and Participation

It is important to discuss with patients the advantages and limitations of minimally invasive surgery so they are able to participate in the decision-making process. Patients should be well-informed before surgery of the difficult scenarios requiring conversion to open surgery for successful outcomes. This should not be viewed as a failure of the procedure or as a shortcoming of the surgeon. Rather it should reflect the judiciousness and ability of the surgeon

to instinctively adapt in the best interest of the patient. Finally, it must be emphasized that a good surgical candidate has a high chance of successful clinical outcome regardless of surgical approach.⁴⁵

Outcomes

The MSD described by Caspar⁵⁷ in 1977 has long been regarded as the gold standard approach for lumbar discectomies. Newer procedures are often evaluated in terms of efficacy, safety and outcomes in relation to this established technique. The current literature on MED suggests comparable short and intermediate term outcomes compared to both open surgery and MSD.^{52,58-60} Reported advantages of MISS procedures include less blood loss, smaller incision sizes, reduced length of hospital stays and decreased postoperative pain. Whether this translates into superior clinical outcomes has not yet been conclusively proven. Very few long-term follow-up studies are currently available evaluating the efficacy of these procedures. In a recent 10-year comparative study, Lee et al.⁶¹ observed no statistically significant differences between MED and MSD in terms of clinical and radiological outcomes, beyond an initial 3-month postoperative period. Other studies also failed to demonstrate any significant advantage for minimally invasive discectomy and decompressive procedures.^{62,63} More well-designed studies are needed before a definitive conclusion can be made regarding differences in outcomes.

In conclusion, minimally invasive microendoscopic techniques are safe and effective and comparable to standard open techniques in terms of patient-based outcome measures. Proper patient selection remains a crucial factor in achieving successful outcomes and minimizing complications using these techniques.

KEY POINTS

- The philosophy of MISS revolves around minimizing tissue trauma and the preservation of paraspinal muscle function and posterior spinal osseoligamentous integrity.
- Various minimally invasive approaches and techniques to the lumbar spine have been described and are used in practice. MISS using tubular retractor systems are based on the posterior interlaminar/translaminar approach.
- The indications for tubular retractor-assisted MISS for lumbar surgery have expanded greatly in recent

years, from simple discectomy to multilevel decompression and interbody fusion procedures.

- Patient selection is one of the most important factors in terms of optimizing results and reducing procedure-related complications.
- The techniques, at present, are relatively safe and afford comparable efficacy to the traditional open approaches. However, superiority over open surgeries in terms of clinical outcomes is currently unproven.

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Provides a systematic review of whether minimally invasive procedures for the spine have decreased complication rates compared to the traditional open procedures.

Minimally Invasive Transforaminal Lumbar Interbody Fusion

William Tally, Giuseppe MV Barbagallo

Snapshot

- » Technique
- » Complications

- » Outcomes

While the end of the last century may be deemed, “The age of the fusion cage”, the beginning of the new one has focused on a less traumatic delivery system for fusion hardware. Certainly lessons learned from studying results of open fusion surgery have shown complications compromising outcomes. Iatrogenic muscle injury leads to considerable postoperative pain and prolonged disability often with lengthy hospital stay.¹⁻⁴ Traditional open procedures are associated with significant blood loss often requiring transfusion.^{5,6} The accompanying soft tissue trauma is likely associated with adjacent segment disease.⁷

The above-mentioned problems associated with open surgery to fuse lumbar vertebrae have lead to ongoing exploration of less traumatic minimally invasive techniques. The hypothesized advantages of such approaches include: less blood loss, less postoperative pain; shorter hospital stay and faster time to narcotic independence.^{8,9} By definition these approaches are designed to preserve postoperative muscle volume.

With each attempt to minimize the trauma related to the surgical approach for delivery of interbody fusion cages, a new list of problems seem to arise. Posterior lumbar fusion, for example, increased fusion rates over posterolateral fusion, but at the expense of increased risk of neurologic injury. Transforaminal fusion again may decrease the incidence of neural injury compared to posterior lumbar interbody fusion, but at the risk of

iatrogenic instability. Still, as with all posterior approaches neural injury remains a concern.¹⁰

The concept of indirect neural decompression with anterior fusion is not new. Such procedures are designed to increase spinal canal volume and neuroforaminal surface area without risk of injury to the neural structures within the canal.^{11,12} None the less, anterior lumbar fusion does pose a risk for vascular injury as well as sexual dysfunction.^{11,13} Anterior fusion procedures achieve restoration of lordosis and disc height. A wide access to the disc space for thorough discectomy and end plate preparation provides ample space for large cages to increase fusion rates. This leads to their continued use.

Lateral lumbar interbody fusion techniques offer many of the advantages of anterior interbody fusion such as ability to restore lordosis and disc height, and insert large cages, but do so with less risk to the great vessels. There is also less risk to the sympathetic neural structures making the complication of retrograde ejaculation unlikely. These approaches have limited utility addressing pathology at L1-L2 and L5-S1. The approach itself, however, puts the lumbar plexus at risk for injury. Femoral nerve injury, thigh weakness, meralgia paraesthetica from genitofemoral nerve injury, quad and hip flexor weakness are but some of the reported complications just from traversing the psoas muscle.¹⁴ The standard risks of fusion surgery such as nonunion, subsidence, implant migration remain. Clearly approaching the intervertebral area for fusion preparation has some inherent risk.

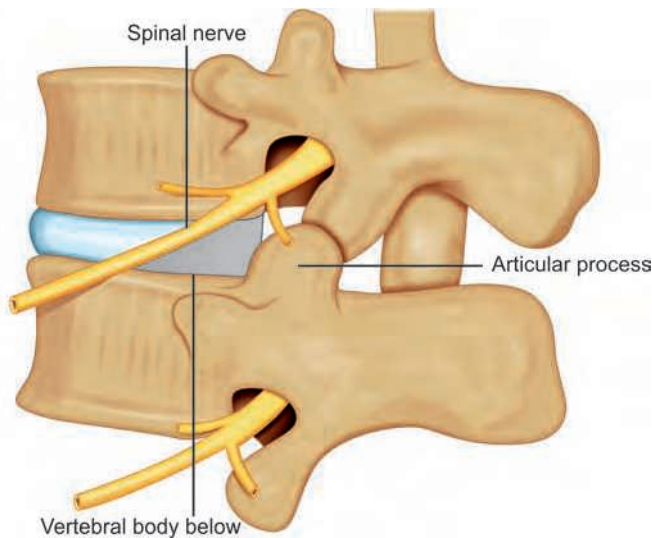


Fig. 133.1: Kambin's Triangle: Boundaries are the superior articular process, the exiting nerve root and the vertebral body below.

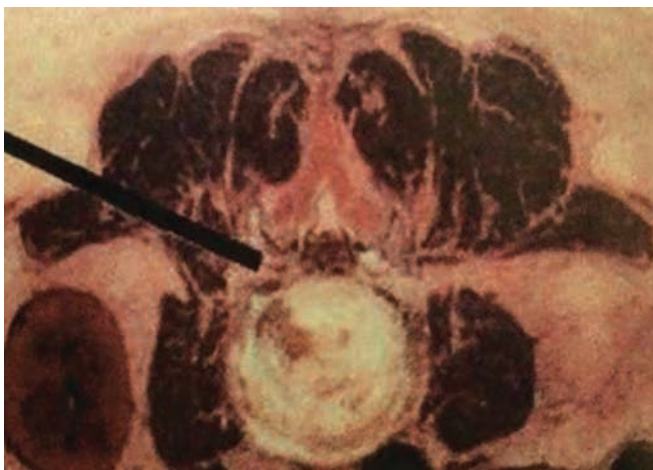


Fig. 133.3: Surgical access corridor: Demonstrates muscle preserving approach between iliocostalis and quadratus lumborum.

In attempt to find a safer access to the disc space, we have been utilizing Kambin's triangle. This space is bound by the superior articular process posteriorly and the superior end plate of the vertebral body below. The roof or hypotenuse of the triangle is the exiting nerve root. the dimension of the space average 12.3 mm in height. The hypotenuse is 23 mm long, and the inferior border is 18.9 mm on average. In assessing feasibility for passage of instrumentation, cannulas up to 10 mm can safely pass into this space¹⁵ (Fig. 133.1).

Although this represents a new fusion access corridor, Kambin's triangle has been shown as a safe path for

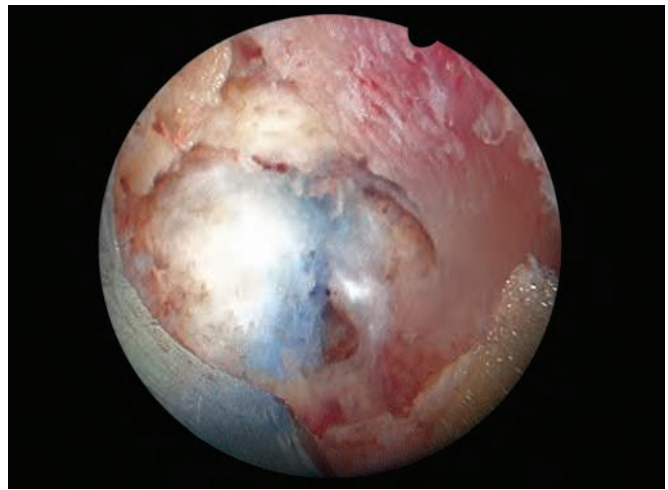


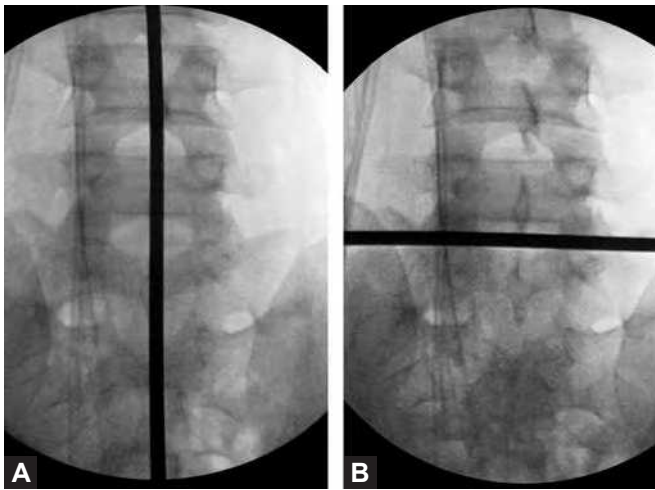
Fig. 133.2: Neuroforamen and exiting nerve root directly decompressed for procedure.

discectomy since the 1970s. Whether performed through cannulas,¹⁶ automated suction devices,¹⁷ or with lasers for disc decompression¹⁸ tens of thousands of these cases have been performed with complication rates lower than 1%. Advances in endoscopic visualization and instrumentation have expanded the indications for these procedures to include removal of extruded migrated herniation fragments, and to relieve stenosis by bone removal with endoscopic burr systems (Fig. 133.2).

This access to the disc space is the least traumatic to the musculature. It utilizes the natural plane between the iliocostalis and quadratus lumborum muscles. Complete discectomy and endplate preparation are accomplished through an 8 mm cannula (Fig. 133.3).

TECHNIQUE

To accomplish discectomy and cage insertion safely through Kambin's triangle, care must be taken to identify the appropriate skin origination point for cannula insertion. It is also imperative to have all instruments parallel the inclination of the disc space so as to not violate the vertebral body endplates and risk cage subsidence. The skin window to the disc is established by a modification of the technique described by Yeung. With the patient appropriately positioned on a frame in the prone position the disc center is marked on the skin in the horizontal and longitudinal axis (Figs. 133.4A and B). Next, in a true lateral projection, the disc inclination is marked on the patient's side (Fig. 133.5). This inclination must be parallel to the disc space. Instruments are inderted along the path marked by the



Figs 133.4A and B: Disc center determined on AP fluoroscopy.



Fig. 133.5: Disc inclination determined with true lateral image.



Fig. 133.6: Skin window for disc access: The initial start point intersects the inclination line of the disc. The distance off the midline is the distance from dorsal skin to the disc center at L3-L4 measured from lateral inclination X-ray. For L4-L5 and L5-S1, the distance is from dorsal skin to junction of anterior and middle one-third of disc.

inclination line. As such, entry to the disc spaces at L5-S1 and L4-L5 typically is cephalad to the disc target, and L12 and L2-L3 disc spaces are usually targeted from a more caudal starting point. The distance from the midline to make our skin incision is also determined by lateral fluoroscopic image and is the distance from the dorsal skin to the junction of the middle and anterior third of the disc at L4-L5 and L5-S1. For L1-L2 and L2-L3, our starting point is closer to midline, the distance from dorsal skin to the junction of the anterior and middle third of the disc. It is important to note that the skin window is not necessarily in line with the disc location, but rather is the distance off center that intersects our inclination line (Fig. 133.6).

As this technique is the most tissue sparing way to reach the intervertebral space muscle preservation is considered at each step. Prior to skin incision, the authors recommend inserting a spinal needle through Kambin's triangle. This helps to confirm our inclination of approach parallels the disc space and that our trajectory will allow crossing the midline of the disc as close to 45° as possible to allow symmetric restoration of disc height. Once confirmed, a 12–15 mm skin incision is made. We prefer to penetrate the lumbar fascia with a blunt dilator to minimize bleeding and muscle trauma.

The protocol for this procedure calls for a blunt tip electromyography (EMG) probe to be used as the initial instrument to pass through the working safe zone. Once on the disc the probe is stimulated. The minimum threshold of safe distance from the exiting nerve root is a lack of neurologic response from a 3 milliamp stimulus. This confirms at least a 1.5 mm space between the exiting nerve root and the probe. Usually higher thresholds are obtained implying greater distance from the neural structures. If a neurologic response is elicited by low stimulus, the probe should be backed out of Kambin's triangle and repositioned. It is critical to not proceed with this procedure if safe passage past the nerve is not demonstrated. Should this situation arise, two options are available: conversion to traditional TLIF, or foraminal decompression. One of the authors, has reported previously on endoscopic foraminal decompression to increase the space available for instrument passage past the exiting nerve root.¹⁹ This technique requires specialized endoscopic equipment not routinely used for Kambin's triangle fusion surgery. It has been demonstrated to provide

safe access to the disc space and lessen dysesthesia incidence (Fig. 133.7).

After safe access to the disc space is confirmed, a sheath is advanced over the EMG probe and anchored on the disc and a guidewire is placed through this into the disc space. At this time the trajectory of the instrumentation is confirmed with AP and lateral fluoroscopic images. The guidewire should ideally be in the disc center on both images to assure as close to a 45° angle path across the disc. If this is not the case, raising or lowering the hand allows adjustment of the trajectory.

Once the guidewire is safely inside the disc, blunt dilators are used to divide the lumbar musculature. The

tubular access working cannula is then anchored in the disc space over the dilator using a mallet. Ideal position is confirmed with fluoroscopy when the cannula is at the medial border of the pedicle on AP image and about 25–30% into the back of the disc on lateral image. This roughly coincides with the annular nuclear junction.

From this point, all disc decompression and endplate preparation is accomplished through this 8–9 mm outer diameter tube. Options exist depending on device used to do disc work using expanding disc shapers and loop curettes through the tube with pituitary rongeurs to remove debris, or to do disc work endoscopically. The endoscope does allow for removal of extruded and migrated fragments as part of procedure (Figs. 133.8A to D).

Once endplate preparation has been accomplished, bone grafting is done through filler tubes through our access cannula to restore disc height and provide anterior column support. If desired trial prostheses may be placed before grafting, however as the expansile discectomy instrument increases its size in 1 mm increments, most surgeons use this device to determine implant size. By doing so, fewer passes of instruments past the exiting nerve root are done, so less nerve root retraction is required.

The fusion implants presently available do not pass through the working cannula. As such, after bone grafting, the blunt guidewire is again placed into the disc space. By placing the wire through the initial blunt dilator we assure central position of the guidewire. Care is then taken to remove the dilator and working cannula without displacing the guidewire.

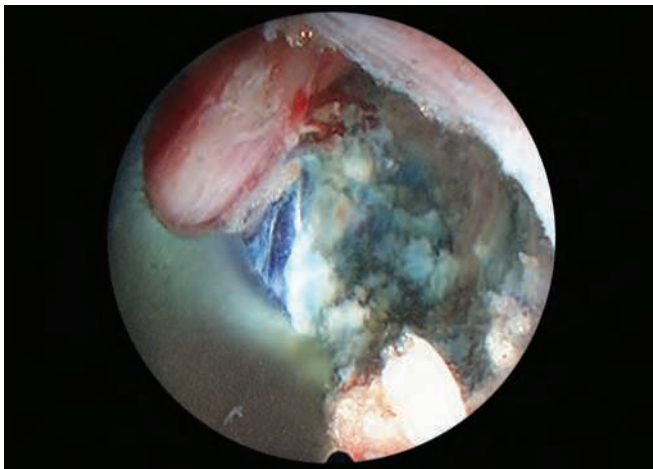
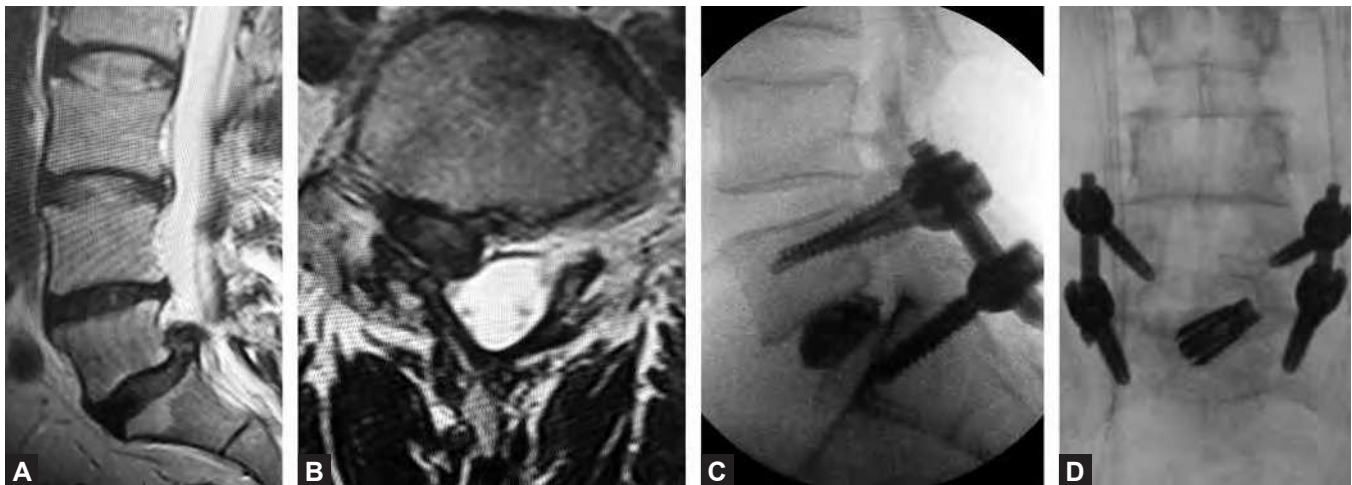
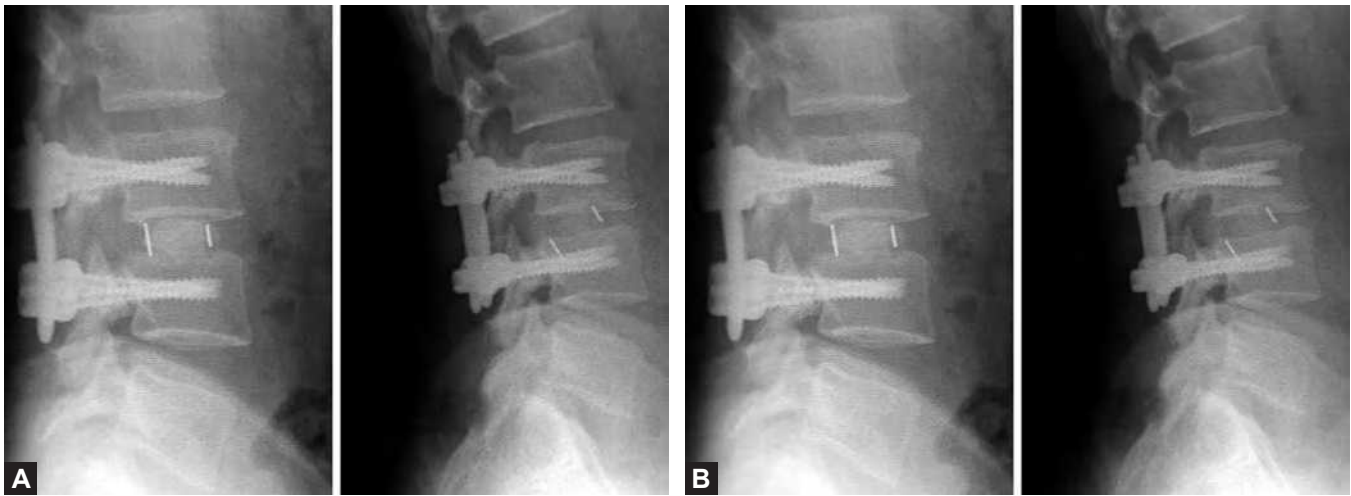


Fig. 133.7: Foraminal decompression: endoscopic images of foraminotomy.



Figs. 133.8A to D: Expanded indications for the technique: Use of endoscope allows additional decompression within the canal and offers opportunity for direct and indirect decompression.



Figs. 133.9A and B: Cage subsidence: Early and late postoperative X-rays demonstrate cage subsidence.

Implant insertion is next done. The implant is passed over the wire through Kambin's triangle until it is against the disc. Care must be taken to avoid guidewire advancement by bending the wire over the inserter handle. Before final insertion, make sure the implant is correctly rotated to its final resting position. The cage can then be advanced into the disc space. The bullet tip of the implant will retract the exiting nerve root like the initial dilator and will gradually restore disc height. Final position should show the implant centered on the spinous process in the AP fluoroscopic image, and centered in the disc space laterally.

These fusion procedures are not stand alone implants and should be augmented with posterior fixation. Both authors use bilateral pedicle screw fixation with compression for additional fixation.

COMPLICATIONS

As is the case with all emerging technology, complications do arise. Fortunately, due to the proven safety of the Kambin's triangle approach, no serious adverse effects have been reported. There have not been any bowel or visceral injuries, nor have there been any vascular complications. This technique does not put the lumbar plexus at risk. Dural tears or epidural scarring has not occurred. Dysaesthesia remains the most common complication and occurs in 30% of cases. It is almost always transient, but if poorly tolerated by patients can be lessened with transforaminal nerve blocks and gabapentin. Advising patients preoperatively of potential new or increasing leg pain for a period of time post operatively makes these complaints minor.

Nonunion remains an unanswered dilemma in 10% of cases. Perhaps better bone graft substitutes may lessen the incidence.

Cage subsidence is also seen in 15% of cases (Figs. 133.9A and B). Care in avoiding violation of the end plate during preparation lessens the incidence of this, as does implant insertion parallel to disc space. Expanding and lordotic implants are being evaluated to see if this may decrease the frequency of this adverse outcome. It is important to not oversize the implant, as this may lead to endplate failure, which again is associated with cage subsidence. Ultimately, the dimensions of Kambin's triangle limit implant size and fusion footprint, as such, in cases of very portic bone alternative techniques should be considered.

Hypesthesia lasting longer than three months is seen in 10% of cases. Typically this is seen as slight diminution of sensation in the L5 nerve root distribution after L5-S1 surgery particularly in cases with a high iliac crest or narrow foramen.

Implant failure or fracture of a 2 mm corner of an implant occurred in one case while attempting to distract a very collapsed L5-S1 disc space. The small fractured fragment was easily removed not affecting the implant integrity. As a caveat, make sure inserter is firmly attached to implant, as the fracture occurred at the screw thread junction.

Motor weakness lasting longer than three months is not common. We have only had 2% of cases with residual weakness of the extensor hallucis muscle after L5-S1 fusion.

Blood loss averages 50 cc or less for these procedures. No patient has needed a transfusion.

Infection is rare as the access corridor leaves no dead space. We have had no early and only one delayed infection in a non-controlled diabetic with blood sugars over 500.

Implant migration has occurred in one case of nonunion. This implant was removed by screwing the threaded part of the inserter into the cage through the original incision. The implant can then be retrieved. The procedure was then revised through the original technique achieving fusion.

OUTCOMES

We have successfully performed this procedure in 100 patients addressing pathology from L1-L2 to L5-S1. Visual analog score (VAS) back and leg improved by greater than 5 grades. All procedures are done in outpatient or overnight setting. About 90% of patients would undergo the procedure again or recommend it to a friend. Return to work is typically in three to six weeks depending on job summary. Narcotic independence is three weeks or less.

SUMMARY

Kambin's triangle allows reliable safe access to the disc space for decompression and interbody cage insertion. While minor complications do arise, serious ones are avoided. Due to the limitations of existing hardware, nonunion and cage subsidence do still occur.

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Minimally Invasive Deformity Surgery

Michael Y Wang, Hamadi Murphy, Mayan Lendner, Christie Stawicki, Taolin Fang, Alexander R Vaccaro

Snapshot

- » Context
- » Lateral Interbody Fusion with Percutaneous Screws
- » Multilevel Minimally Invasive Surgery Transforaminal Lumbar Interbody Fusion
- » Mini-Open Pedicle Subtraction Osteotomy
- » Surgical Technique
- » Future Directions

CONTEXT

Modern medicine and technology have created an unprecedented level of care, comfort, and convenience for citizens of developed nations. Concomitantly, the percentage of elderly patients has increased significantly. In 1990, there were 37,306 Americans Centenarians, but it is estimated that by 2050 there will be 4.2 million persons aged 100 or older (Fig. 134.1).¹ These changes will impact providers of spinal care significantly, as degeneration of the spinal column is associated with increasing age. Data from the

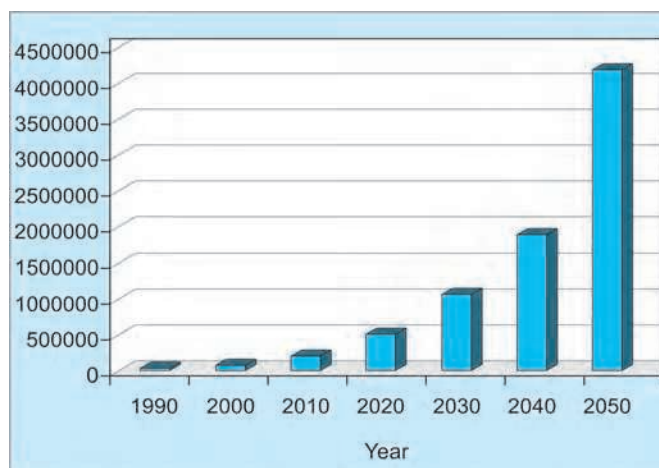


Fig. 134.1: Number of US centenarians.

National Health and Nutrition Examination Survey (NHANES) study estimates the prevalence rate of scoliosis at 8.3% in adults (defined as $>10^\circ$ curves).² More importantly, the prevalence and severity of spinal deformities increase with age and loss of bone mineral density. Thus, spinal surgeons will be increasingly caring for elderly patients with adult spinal deformity (ASD).

Adult spinal deformity remains a challenging proposition for the spinal surgeon. A combination of factors results in high intra- and postoperative complication rates with the surgical correction of ASD. These factors include an increased number of medical comorbidities, patient deconditioning due to pain and immobility, associated osteoporosis, a rigid skeletal deformity, and abnormal spinal anatomy.^{3,4} In addition, the surgical intervention necessary to treat these patients is typically a long-segment fusion with fixation and osteotomies, often in concert with interbody fusion or anterior access. This results in a painful, debilitating operation that requires prolonged anesthesia, long recoveries, and extended hospital stays. Thus, it is not surprising that reports from expert deformity surgeons reveal a high rate of serious complications. For example, in Kostuik's series of 361 patients, the 30-day mortality rate was 2.4%.⁵ A recent report by Smith et al. analyzed data from the Spinal Deformity Study Group showing that 26.2% of their 206 patients suffered a minor complication, and 15.5% suffered a major complication.⁶

Minimally invasive surgery (MIS) alternatives were developed over the past decade in an attempt to manage these patients with lower surgical morbidity rates.⁷⁻⁹ The degree to which this has been successful to date is a matter of considerable debate. However, the laudable goals of reduced blood loss, lower narcotic consumption, faster mobilization, and reduced infection rates have been effectively demonstrated in short segment MIS spine surgeries, such as MIS transforaminal lumbar interbody fusion (TLIF) when compared to traditional open operations. If these effects can be translated to the ASD population, MIS techniques would represent a significant advance.

A variety of techniques have been developed in an attempt to apply MIS methodologies to correct coronal and sagittal deformities. This chapter will outline three different categories of techniques, each with potential advantages and drawbacks. It should be understood that subtle differences in technique exist between surgeons and centers, and these nuances can be critical to successful patient outcomes.

LATERAL INTERBODY FUSION WITH PERCUTANEOUS SCREWS

One of the more popular minimally invasive techniques for treating ASD is a lateral interbody fusion at multiple lumbar levels followed by percutaneous screw placement. This method was popularized following the introduction of a method innovated by Pimenta for accessing the disc through a direct lateral trajectory.¹⁰ This was similar to open lateral interbody fusion through a thoracoabdominal approach in that the spine was accessed through the retroperitoneal space, which had already been effectively used for years to access the L1-L5 disc spaces. However, the advent of tubular dilator retractors and the development of continuous running electromyography allowed the surgeon to use only a small incision and to access the intervertebral disc through the muscle belly of the psoas. Safe navigation around the lumbar plexus was critical to this technique.

With the patient in lateral position, multiple disc spaces could be accessed and treated with significant improvement in coronal alignment and scoliosis. While stand-alone constructs have been used, most significant deformities are treated with supplemental fixation, which was now possible with the use of percutaneous pedicle screw-rod constructs (Figs. 134.2A to F). Detailed descriptions of the nuances of this method can be found in other chapters of this textbook. This technique has been applied with much

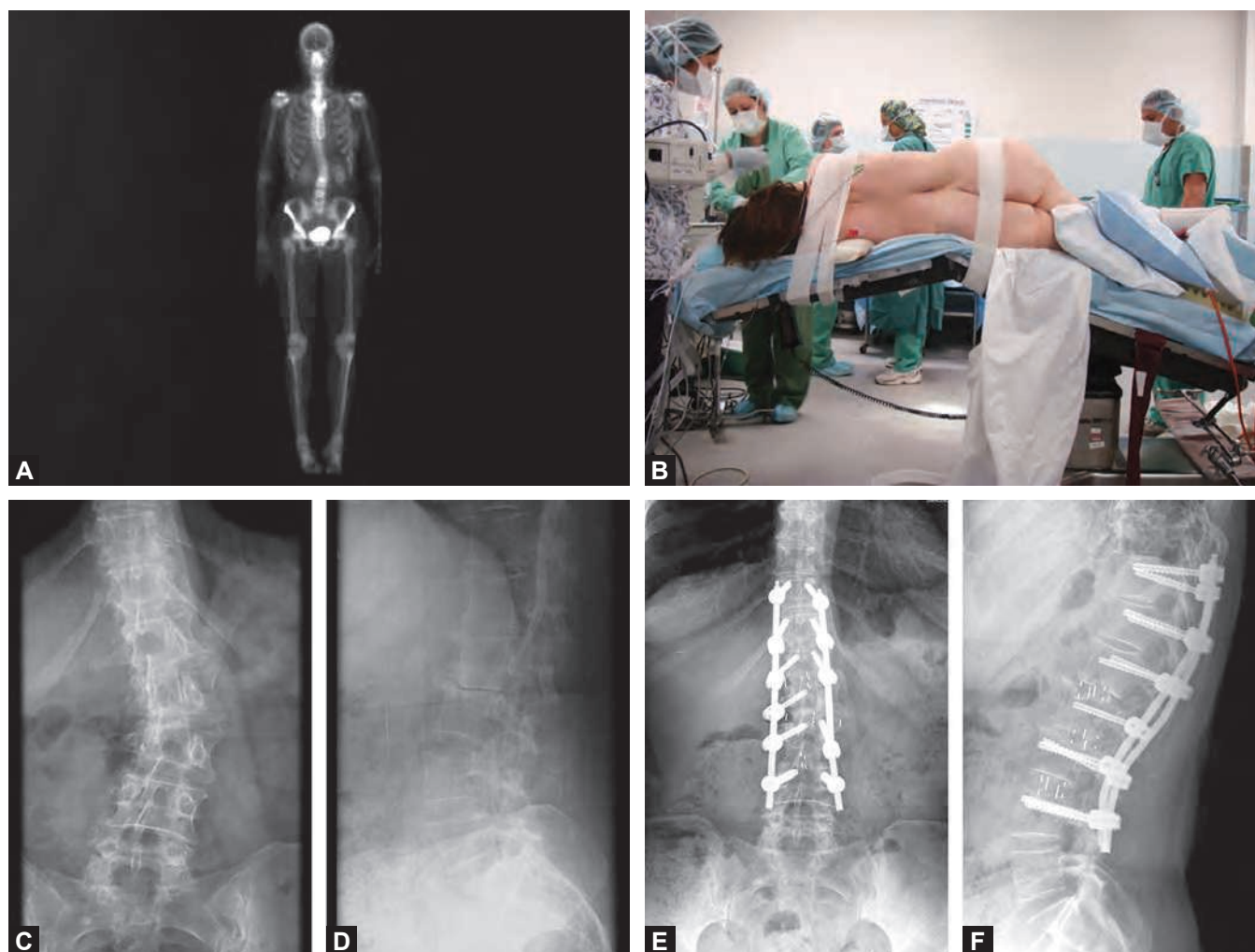
enthusiasm and has proven excellent for treating local degenerative arthritis, restoring foraminal height, achieving indirect neural decompression, and correcting coronal deformity.^{7,9,11-13} In addition, the results with these surgeries in the published literature have generally been associated with reductions in total blood loss and almost no cases of wound infection.

However, four significant drawbacks remain with this approach. First, the need for lateral as well as prone positioning prolongs anesthetic time in this medically compromised patient population, as two-position surgery (supine then prone) has traditionally been very time-consuming. Some surgeons have attempted to circumvent this problem by performing percutaneous screws, while the patient is in the lateral position. This can be technically more challenging for fluoroscopic imaging and is more efficient with the use of frameless navigation. Others object to the non-ergonomic work posture for the surgeon. A second solution has been to stage these surgeries. Following the direct lateral operation the patient is allowed to convalesce, and this will allow the surgeon to ascertain whether any indirect neural decompression has been effective. This allows the second prone surgery to be accompanied by a direct neural decompression (laminectomy or foraminotomy) if needed. This approach, of course, adds significant cost and subjects the patient to two anesthetic episodes.

The second major drawback has been the relative inability to treat the lumbosacral junction from the lateral approach. Surgeons desiring to fuse this area have in the past combined the procedure with an MIS TLIF or transsacral interbody screw. Others have opted to even take the extreme measure of drilling through the iliac crest to access L5/S1. Regardless, it is clear that access to the more caudal spinal levels results in higher rates of inadvertent injury to the lumbosacral plexus, even with the use of neuro-monitoring.^{14,15}

In addition, the inability to treat the lumbosacral junction can be a critical downfall if the patient has a significant fractional curve. This curve, at the base of the spine, can set the plane of the midlumbar spine at an angulation. Subsequent correction or straightening of the midlumbar curve (which is usually the more obvious or larger curve) can throw a previously coronally aligned patient out of balance. Lack of care and attention to spinal balance and the fractional curve can thus result in worsening of spinal alignment after surgery.

The third drawback of this approach has been that it is unproven for correcting severe, stiff curves of $>50^\circ$.



Figs. 134.2A to F: Case example of using direct lateral interbody fusion technique for treating adult scoliosis. (A) The patient's single photon emission computed tomography bone scan shows back pain emanating primarily from arthritic changes in the upper lumbar spine. (B) Positioning in the operating room allows for a lateral jack knife position that opens the concavity of the curve. (C to F) Pre- and postoperative X-rays showing a T11-L4 minimally invasive surgery instrumented fusion with lateral interbody cages at L1–L4. Facet fusion is performed at T11-L1.

In series reported to date, the majority of curves have had a Cobb's angle of $<30^\circ$. In Uribe's series of 25 patients only four patients had a scoliosis of $>30^\circ$.¹² In Anand's series of 28 patients, Cobb's angles ranged from 15° to 62° , but averaged only 22.3° .¹¹ In Kanter's series of eight patients, the curves were more severe. Preoperative Cobb's angles ranged from 18° to 80° and averaged 38.5° . However, this series utilized an open second posterior approach, allowing for posterior column osteotomies and open screw-rod manipulation techniques to assist with curve correction.¹⁶ Advances in the application of lateral release and cage insertion techniques will likely result in the ability to treat greater curvatures, as this landscape is still evolving.

Finally, this approach has resulted in only minimal or modest improvements in lumbar lordosis. In the recent series of 35 patients by Acosta et al., the lateral MIS approach allowed for a Cobb's angle correction from 21.4° to 9.7° , a statistically significant improvement.¹⁷ However, lumbar lordosis only changed from 42.1° to 46.2° despite improvements in interbody height. Overall, the global sagittal alignment was unchanged. This is similar to the finding of a 5° improvement in global lordosis published by Karikari et al.¹⁸ Given the importance of maintaining or improving sagittal parameters in the ASD patient population, this represents an important deficit in this particular MIS technique for addressing ASD.

MULTILEVEL MINIMALLY INVASIVE SURGERY TRANSFORAMINAL LUMBAR INTERBODY FUSION

One- and two-level MIS TLIF has become very popular for treating spinal stenosis, disc reherniation, spondylolisthesis, and other degenerative spinal disorders. Part of the appeal of MIS TLIF has been that it allows for the complete treatment of a spinal segment, including neural decompression, interbody fusion, and stabilization. The recent literature has supported the notion that when compared with open TLIF, the MIS TLIF can generally be regarded as accomplishing the same goals of surgery, with attendant decreases in blood loss, infection rates, and hospital length of stay. Whether the clinical significance of these differences is meaningful can still be debated, but the effects are likely to be real.

Multilevel open TLIF has also been shown to be an effective strategy for managing less severe cases of spinal deformity. A previous clinical series by Scheufler et al. demonstrated the efficacy of multilevel MIS TLIF to obtain improved lordosis in the ASD population.⁸ In that series of 30 patients image guidance was used to plan and place hardware for interbody as well as transpedicular fixation. An excellent mean correction of 31.7° and 44.8° in the coronal and sagittal planes, respectively, was achieved. Thus, the use of TLIF for deformity surgery as described by Heary and Karimi¹⁹ appears to afford the opportunity for improved deformity correction. This procedure at multiple levels has been improved with the use of modern expandable cages and percutaneous pedicle screws (Figs. 134.3A to E). One of the appeals of this approach has been that with a single position surgery, the complete operation can theoretically be accomplished in a reasonable timeframe, limiting the anesthetic risks to the patient.

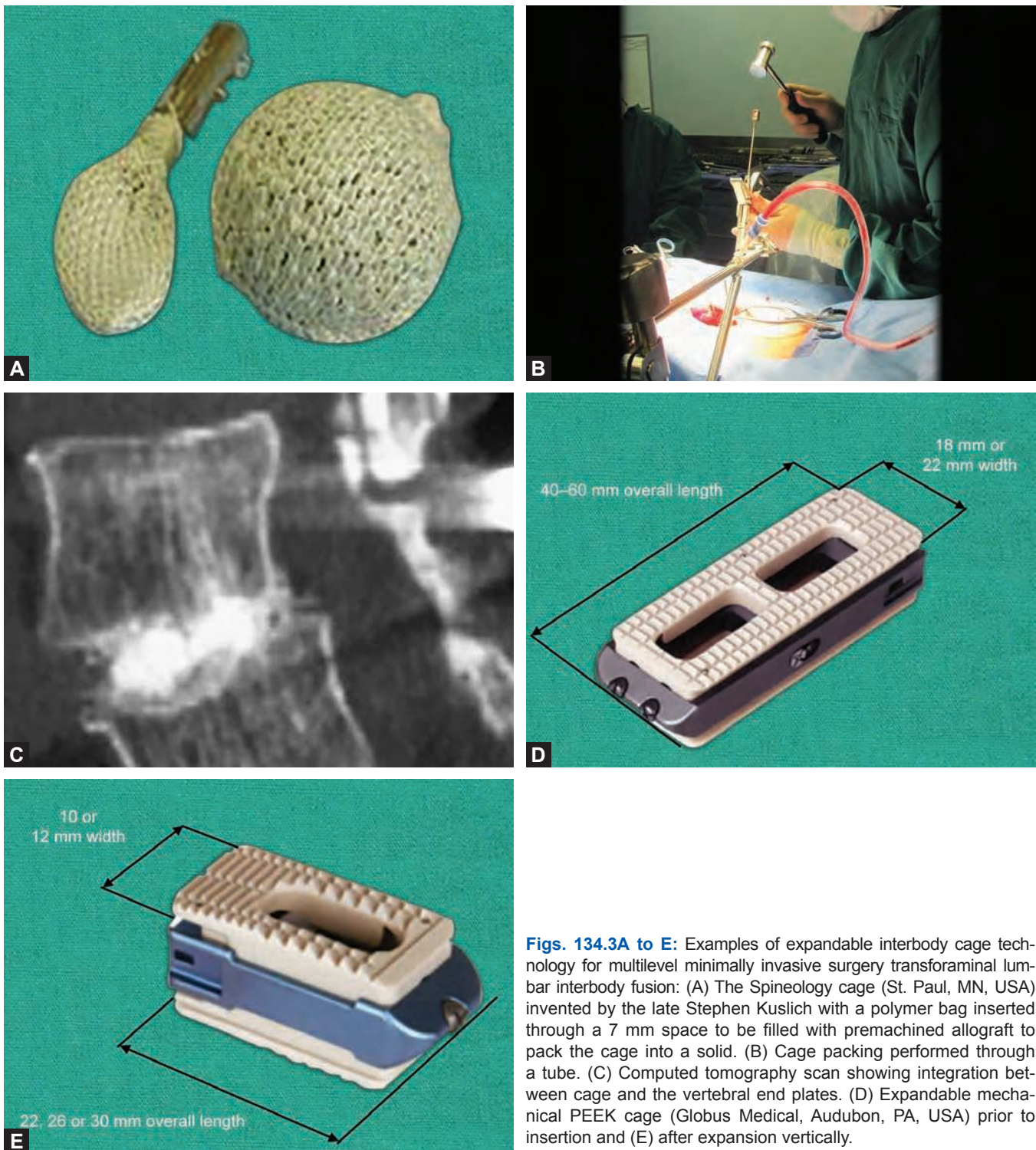
Surgical Technique

The surgery is accomplished in the prone position under general anesthesia. Positioning on the Jackson table is critical to allow the belly to hang and increase lordosis after the releasing osteotomies and disc removal. A single midline incision is made over the segments to be treated. This technique prevents the creation of undue cosmetic defects, problems often seen with multiple stab incisions. A plane is created above the superficial fascia so that percutaneous screws can be placed with minimal disruption of the soft tissue envelope. Only one side of the spine is accessed to allow for facetectomies and interbody cage placement. A subperiosteal dissection is then taken to the lateral facet

joints only on the side of approach for the MIS TLIFs, and the contralateral side is not exposed below the fascia. The choice of which side to approach from will depend on the type of deformity, clinical symptoms, and the goals of surgery. Typically, approach is made from the concavity of the fractional curve (the curve at the lumbosacral junction) which is the same side as the convexity of the major curve (which is typically midlumbar).

Following exposure and confirmation of spinal levels the facet osteotomies are performed from lateral to medial across the superior facet just rostral to the pedicle. A cerebellar retractor is used to elevate the soft-tissue envelope. A midline laminectomy is not typically performed unless there is severe central canal stenosis that requires direct decompression. An osteotomy is performed at each MIS TLIF level. The operating microscope is then used to more clearly visualize the critical structures. Bone, joint, and soft tissue removal is then taken medially up to the lateral border of the ligamentum flavum at a minimum. The lateral annulus is then found just rostral to the pedicle and the surrounding veins are coagulated using bipolar cautery. An incision is made through the annulus and insert-and-rotate shaver dilators are used to remove the intervertebral disc, with great care taken to preserve the cortical vertebral end plates. This is particularly important in the setting of osteoporosis. In addition, the medial angulation of the approach is critical and will differ by level. In surgeries where the approach is on the side of the concavity (simple curves without a fractional component) the disc removal will be predominantly ipsilateral in order to distract the interspace that has been closed down. In surgeries where the approach is on the side of the convexity of the major curve (this is also the side of the concavity of the fractional curve), the contralateral side of the disc is accessed and removed so that interspace height can be restored on the collapsed portion of the major curve.

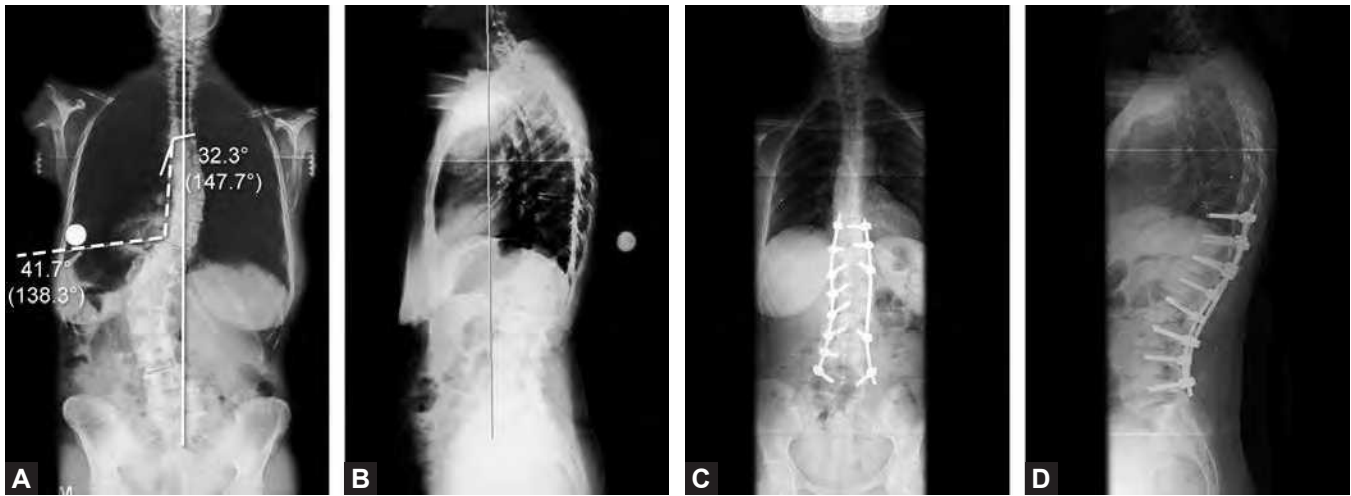
Once complete disc removal has been accomplished, fusion adjuvants are placed into the disc space. Autograft bone from the facetectomies is used, as well as rh-BMP-2 (InFuse, Medtronic Sofamor Danek, Memphis, TN, USA) at a dose of up to 1.05 mg/level. A 25 mm Optimesh (Spineology, Minneapolis, MN, USA) cage may be inserted and internally filled with allograft granular matrix. The device is inserted through a 7-mm diameter portal and inflated within the disc space, restoring intervertebral height. It should be noted that both of these products used in this setting are considered “off label” by the Food and Drug Administration. Once filled and inflated, the cages are crimped shut and the nerve roots are inspected to ensure there is no impingement.



Figs. 134.3A to E: Examples of expandable interbody cage technology for multilevel minimally invasive surgery transforaminal lumbar interbody fusion: (A) The Spineology cage (St. Paul, MN, USA) invented by the late Stephen Kuslich with a polymer bag inserted through a 7 mm space to be filled with premachined allograft to pack the cage into a solid. (B) Cage packing performed through a tube. (C) Computed tomography scan showing integration between cage and the vertebral end plates. (D) Expandable mechanical PEEK cage (Globus Medical, Audubon, PA, USA) prior to insertion and (E) after expansion vertically.

Percutaneous screws are then placed by cannulating the pedicles using Jamshidi needles. This is accomplished primarily using anteroposterior (AP) fluoroscopic

X-rays. The technique involves docking the needle tip at the junction of the transverse process and lateral facet joint. The needle is malleted into the bone 2 cm without



Figs. 134.4A to D: (A and B) Preoperative and (C and D) postoperative 36-in standing radiograph for a mini-open T10 to L5 surgery with expandable cages and MIS TLIF at L1–L5.

passing the medial wall of the pedicle on AP X-ray images. This use of the AP technique allows accurate compensation for axial rotation in complex ASD cases. Iliac screws are placed using the obturator outlet view for percutaneous cannulation as previously described.²⁰ For iliac screws, a window is made in the posterior superior iliac spine to avoid screw head prominence. Each needle is then exchanged for a Kirschner wire. An insulating sheath protects the soft tissues, while an awl and tap create the path for the pedicle screw, followed by final screw placement (Viper, Depuy Spine, Raynham, MA, USA).

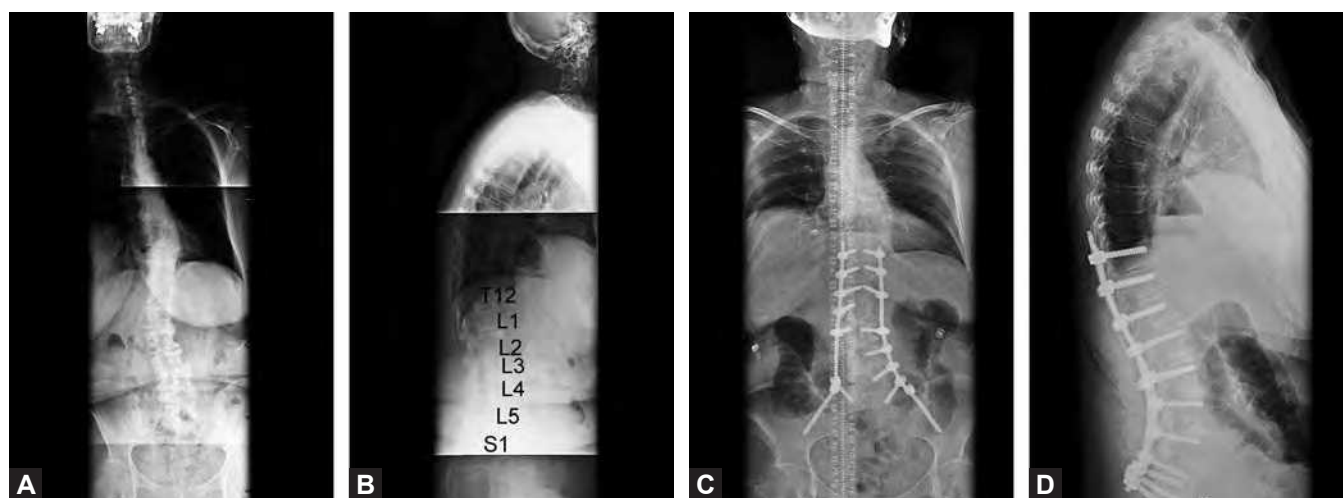
Rods are placed subfascially by passage through the screw extensions. For the levels fused without an interbody cage, a posterolateral fusion is performed. This is accomplished by decorticating the lamina and facet joint through the same fascial incision used for screw placement. Autograft bone and remaining rh-BMP-2 are used to fuse these levels at the thoracolumbar junction. Rod derotation, compression of screw heads along the major curve convexity, and persuasion of the rod to the screw heads are then used to complete the deformity correction. The surgical sites are then closed in standard fashion over suction drainage.

Initial Clinical and Radiographic Results

In a recent clinical series of 25 patients from our institution, patients with curves of 20° or greater were effectively treated. The mean age was 72 years (range of 62–84). Seventeen were women and 8 were men. The mean height and weight were 163.2 cm and 74.3 kg, respectively, with an overall average BMI of 27.8 (range of 21.3–43.5). The

mean weighted Charlson comorbidity score was 1.0 and the combined Charlson score mean was 3.8. A total of 132 segmental levels were treated (mean = 5.28), and 80 interbody levels were treated (mean = 3.2). A total of 256 percutaneous pedicle screws and 14 percutaneous iliac screws were placed. The series was consecutive with no patients lost to follow-up. All surgeries were successfully completed without conversion to an open operation with an average operative time from skin incision to final closure of 273 minutes (range of 180–360). The surgical blood loss as measured by the perfusionist averaged 415.6 mL (range of 200–800 mL). Ninety-two percent of patients were out of bed and ambulating on the first postoperative day, with a mean acute care stay of 5 days (range of 3–8). Eighty percent of patients were discharged home, and 20% were sent to inpatient rehabilitation.

Radiographic outcomes were determined using pre- and postoperative 36" standing X-rays at last follow-up (Figs. 134.4A to D), which was at the 12-month time point. The mean preoperative Cobb's angle was 29.2° + 9.3 (range of 20°–59°). This improved to a mean of 9.0° + 5.0 (range of 3°–21°). This reflected an average of 20.2° of improvement and was a statistically significant improvement ($P < 0.001$). The mean preoperative global lumbar lordosis was 27.8° + 12.9 (range of 6°–53°). This improved to a mean of 42.6° + 12.1 (range of 19°–66°). This reflected an average of 14.78° of improvement and was also a statistically significant improvement ($P < 0.001$). The mean preoperative sagittal vertical axis (SVA) was 7.4 cm + 4.9 (range of 0–17.5 cm). This improved to a mean of 4.3 cm + 5.7 (range of 0–13.0 cm). This reflected an average of



Figs. 134.5A to D: (A and B) Preoperative and (C and D) postoperative 36-in standing radiograph for a mini-open T11 to Iliac surgery with expandable cages and MIS TLIF at L2-S1.

3.2 cm of improvement and was a statistically significant improvement ($P = 0.001$). Fourteen patients had at least 1 cm of coronal imbalance before surgery (range of 0–5 cm). Preoperative mean coronal imbalance was 1.64 cm, improving to 0.72 cm, reflecting a mean improvement of 0.92 cm. Three patients had a worsening of coronal balance due to straightening of the major curve without addressing the fractional curve adequately. Two of these patients worsened from 1 to 3 cm, and one patient worsened from 2 to 3 cm (Figs. 134.5A to D).

Clinical outcomes were ascertained using the numeric pain score (NPS) for the lower extremity (leg and buttock symptoms) and lower back (axial symptoms) on a scale of 1–10 (10 being highest) as well as the Oswestry Disability Index (ODI). Questionnaires were completed in the clinic setting before surgery and afterward at 12-month follow-up. Preoperatively, the NPS for leg pain was 5.1, improving to 1.8 after surgery, reflecting a mean improvement of 3.3. Preoperatively, the NPS for axial back pain was 7.6, improving to 3.4 after surgery, reflecting a mean improvement of 4.2. Preoperatively, the ODI was 44.9, improving to 24.1 after surgery, reflecting a mean improvement of 20.8. There were no cases of neurological worsening except for one patient with new foot dorsiflexor weakness. Of the 16 patients with preoperative nerve root pain, all but one had resolution of leg pain. A total of six complications occurred. Four were hardware-related complications. Two patients had a medial L5 screw breach. In one case, this was removed 2 weeks after the index surgery due to foot weakness. In the other case, the patient only had

numbness and the screw was removed after confirmation of solid bony fusion 9 months after surgery. One patient had an asymptomatic grade II T10 screw breach. One patient had early pullout of one S1 screw that was removed 1 year later after confirmation of successful fusion at L5/S1. Thus, a total of three patients had a return to the operating room during the follow-up period, one of which was acute and two of which were delayed. The fifth complication was a case of acute coronary syndrome occurring in a 79 female who did not suffer from permanent myocardial ischemia. The final complication was a patient with prolonged hospitalization due to severe constipation. This patient was ultimately discharged home.

MINI-OPEN PEDICLE SUBTRACTION OSTEOTOMY

Given the importance of sagittal balance for good clinical outcomes, more powerful methods for improving spinal alignment have been needed. One of the most versatile and powerful techniques for improving sagittal balance is the pedicle subtraction osteotomy (PSO).²¹ Performed with open surgery, this method is associated with a high but unavoidable complication rate due to the significant blood loss, frequent history of previous surgery, advance age, and manipulation of critical neurovascular structures.

We have begun to develop a method for mini-open PSO. Because of the inherent danger of uncontrollable blood loss and neural injury at the osteotomy site, we have chosen to open this area selectively, but the approach limits destruction to the soft tissue envelope and blood loss.

SURGICAL TECHNIQUE

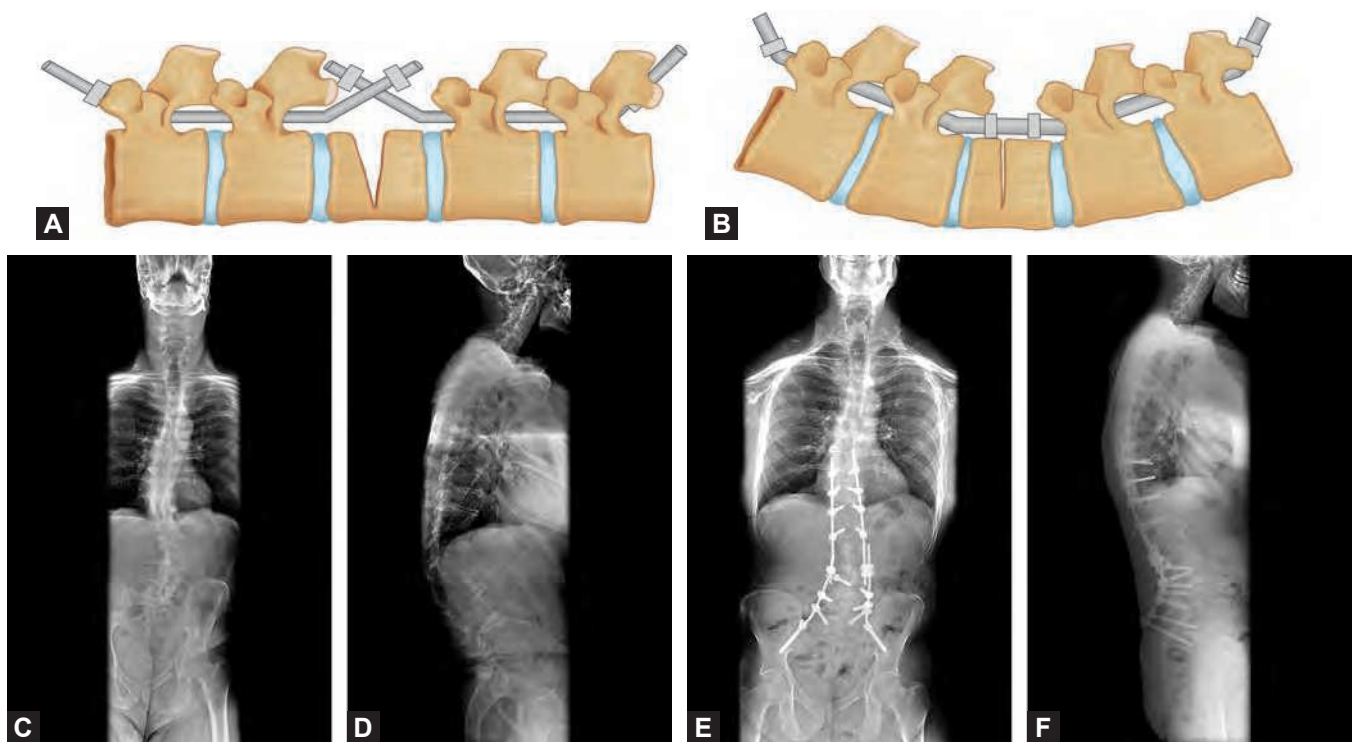
Following intubation, the patient is positioned on the Jackson table. A dorsal midline skin incision is made from the lower thoracic area to the sacrum. Subcutaneous dissection then allows the muscle fascia to be exposed so that all subsequent steps are performed through the fascia. This is preferable to using multiple stab incisions that are cosmetically unfavorable and result in more blood loss. A bilateral subperiosteal dissection is then achieved at the level of the intended PSO. The exposure is taken laterally to the transverse processes at target level. If an interbody fusion below the level of the PSO is desired, then a unilateral subperiosteal exposure of the facet joints is undertaken at those levels to allow for MIS TLIFs.

The target spinous process, lamina, and facets are then removed with a rongeur. The exiting nerve roots are fully exposed and the annulus of the disc above the target pedicle is cauterized with a bipolar and incised with 15-blade scalpel to create an extended PSO. The pedicles are then removed entirely using rongeurs and the high-speed drill. A bilateral decancellation osteotomy was then performed using a series of enlarging curettes to remove

two cones of cancellous bone from the vertebral body. Central bone is removed with a curved curette and the decancellation is extended superiorly into the disc space. Cottonoids are used to dissect and secure the lateral vertebral wall and its associated vasculature. A Leksell rongeur is used to remove the lateral vertebral body wall bilaterally in a wedge-shaped pattern to match the decancellation.

Control of the spine is then achieved by placing percutaneous pedicle screws at least three levels above and below the PSO site. An AP-based fluoroscopic technique is utilized to compensate for axial rotation of the vertebral bodies. The pedicle screw extensions are used to prevent any catastrophic vertebral translation during completion of the osteotomy. The posterior vertebral body wall and posterior longitudinal ligament are removed by retracting the thecal sac medially on each side successively.

After ensuring there is no ventral bone or ligament that might impinge on the thecal sac, the osteotomy is closed. A total of four rods are bent to the same degree of lordotic curvature (approximately 35°). Each rod is passed through each set of screw heads above and below the PSO (Figs. 134.6A to F). This is done as it is not possible to pass a lordotic



Figs. 134.6A to F: Case example of a mini-open pedicle subtraction osteotomy. Artist's depiction of mini-open PSO correction before (A) and after (B) osteotomy closure. (C to F) Pre- and postoperative anteroposterior and lateral 36-in standing radiograph.

rod below the fascia in a kyphotic region of the spine. A rod-to-rod connector is then placed on the end of each rod at the PSO site where the tip is exposed. Set screws are then used to loosely attach each of the four rods to its respective set of screws. By holding each of the four rod holders and forcing them toward each other the osteotomy site is greenstick fractured and the spine is placed into lordosis. At this point, the four rod-to-rod connectors are used to rigidly attach the cranial rod to the caudal rod on the same side. The set screws are fastened tightly and all articulations are then finally tightened.

The nerve roots and thecal sac are then inspected to ensure that there is no neural compression, and any bleeding is controlled with powdered collagen matrix. A small subperiosteal exposure is then achieved on one side at the top of the construct and an interlaminar fusion is created between the top three vertebral segments using autograft bone. The wound is then closed over suction drainage in standard fashion.

FUTURE DIRECTIONS

Significant gaps remain in the MIS spectrum of techniques for treating complex spinal problems in challenging patient populations. Future advances in the ability to mobilize the spine prior to realignment, decrease rates of pseudoarthrosis, safely place implants for fixation, and initiate powerful corrective maneuvers will be necessary to advance the field if an MIS approach is to achieve the results seen with powerful three-column osteotomies. However, improvements in spinal instrumentation, image guidance, and osteobiologics will likely make MIS ASD surgery a viable option for the increasingly aging patient population.

KEY POINTS

- The aging of the US population will result in an increasing need for surgeons to be able to manage ASD in the elderly.
- Several minimally invasive options are available currently for treating ASD, each with its specific benefits and drawbacks.
- Minimally invasive lateral interbody fusion is effective at correcting moderate scoliosis, but restoring sagittal balance has been more elusive.

- Mini-open multilevel TLIF is effective for efficient neural decompression and can yield correction of moderate deformities in both the sagittal and coronal planes.
- Mini-open PSO has promise for correcting cases with more severe sagittal imbalance.

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Use of Navigation in Spine Surgery

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Snapshot

- » Evolution of Spinal Navigation
- » Principles of Spinal Navigation

- » Deformity Surgery

INTRODUCTION

Computer-assisted spine surgery describes a group of technologies that merges preoperative or intraoperative images with three-dimensional (3D) visualization of surgical instruments in real time. Computer-assisted navigation system was first introduced in clinical practice for transpedicular screw fixation in 1995.¹

The use of pedicle screw fixation has improved the mechanical rigidity of the constructs used for spinal stabilization and deformity correction. Pedicle screw fixation enables shorter fusion length and better correction, and achieves three-column fixation and higher rates of fusion. However, pedicle screw fixation is challenging because a significant portion of spinal anatomy is not visible and therefore instrumentation requires inference of spinal anatomy from surface landmarks. The difficulty is further pronounced in situations where the spine is deformed, the landmarks are obliterated and in revision spine surgery.

Traditionally, surgeons relied on their knowledge of anatomy of spine along with images acquired preoperatively and intraoperative fluoroscopy. Intraoperative fluoroscopy is commonly used to assist in localization of skin incision, identification of the proper anatomical level, and confirmation of correct positioning of spinal implants.² Intraoperative fluoroscopy delivers real-time images of the spinal anatomy, but in a single plane and the repeated use of C-arm during surgery results in significant radiation exposure both to patient and surgical staff. Also freehand

and fluoroscopy-guided pedicle screw placement can have misplacement rates up to 30% in the lumbar spine and up to 50% in the thoracic spine.³⁻⁵

In 1987, the Scoliosis Research Society reported an incidence of 3.2% of nerve damage after the use of pedicle screws,⁶ and West et al. in 1991 described a nerve damage rate of 2% associated with misplaced pedicle screws. Using intraoperative fluoroscopy, Castro et al.⁷ reported an incidence of 40% of misplaced screws. The suboptimal position of the screws also has an effect on the implant biomechanics and may lead to early failure. Also of concern is the medicolegal implication of the displaced screws. Safety concerns on the violation of the spinal canal leading to potential harm to vascular, neural, and other vital structures have necessitated the need to improve the accuracy of pedicle screw placement.

Spinal navigation is a computer-based surgical technology that improves intraoperative orientation to the unexposed anatomy during various spinal procedures. Computer-navigated surgery is a subset of computer-assisted spine surgery that is itself a part of both computer-assisted orthopedic surgery (CAOS) and computer-assisted neurosurgery.⁷ The term CAOS was coined by Thomas Kuhn to bring under a single umbrella a number of technologies based on computers such as computer-assisted surgery, medical robotics, computer-navigated surgery, image-guided surgery (IGS), spinal navigation, stereotaxic guidance, and computer-assisted medical intervention.⁸

Image-guided surgery is a combination of image acquisition and processing followed by intraoperative navigation. The overall aim of the spinal navigation procedure is to show the operating surgeon the exact position of the handheld instruments in relation to the bony anatomy, represented on an image displayed in the operating theater. The main goals of IGS are to improve the surgeon's hand-eye coordination, to improve accuracy of implant placement, to reduce radiation exposure to the surgeons, and to shorten the surgical time.

The application of navigation was initially limited to increased accuracy of pedicle screw placement in cervical spine, scoliosis, and revision surgeries. In the last decade, the applications has extended to include surgeries like excision of spinal tumors (e.g. osteoid osteoma and osteoblastoma) and excision of spinal pathologies such as ossified spinal ligaments and osteotomies of spine.

EVOLUTION OF SPINAL NAVIGATION

The current concept of image-guided spinal surgery has its roots in the field of neurosurgery. The concept of stereotaxis, which uses a frame as a reference device to perform invasive procedures, was developed for clinical use by Robert H Clarke and Victor Horsley for treating intracranial pathology.⁹ The specialities of both orthopedics and neurosurgery have been the forerunners in the implementation of IGS.

Nolte et al. in Switzerland developed the concept of interactive navigation of surgical instruments and Merloz et al. in France developed the concept of anatomically based registration using reference anatomical structures detected by intraoperative sensors.^{8,10} Simon and Foley developed this technology in North America.¹¹ They used anatomic landmarks on the dorsal aspect of the spine as fiducially (registration) markers in association with a dynamic reference array (DRA).¹² These anatomic fiducials provided reliable registration accuracy and augmented the flexibility of the system, as the registration points could be added or changed intraoperatively.¹³

Kalfas et al. also performed early investigational research using similar image-guided techniques to improve the safety of lumbar pedicle screw placement.^{12,14} The development of newer concepts of image segmentation, 3D model building, and registration formed the basis of frameless computer-assisted surgery. Major contributions toward this have been from Brown in 1992¹⁵ on two-dimensional (2D) photometric image registration followed by Van den Elsen^{16,17} on 3D-image registration. This led to

the development of second-generation computed tomography (CT) and fluoroscopy-based systems and along with it the use of navigation in complex procedures throughout the spine.

PRINCIPLES OF SPINAL NAVIGATION

Spinal image guidance systems are marketed by various manufacturers. Generally, these systems share the same basic functions and components with differences in software and hardware capabilities.

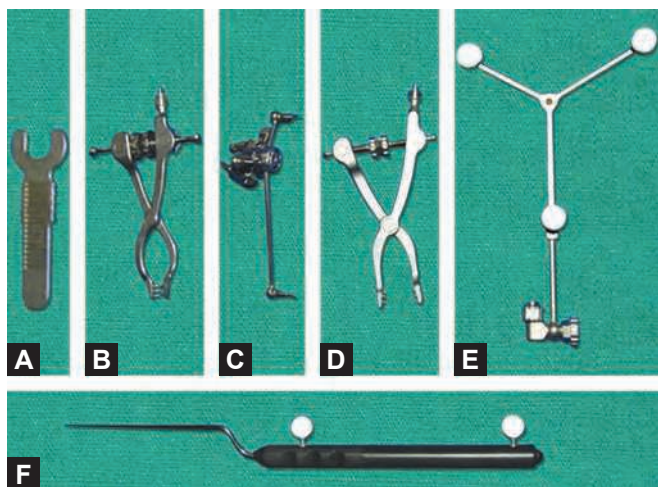
The standard IGS consists of the following components:

1. System of image acquisition and processing
2. Image processing computer workstation interfaced with two-camera electro-optical localizers (Fig. 135.1)

These systems have a referencing device, the DRA, which is attached to the patient during navigation. The DRA has attached LEDs (light-emitting diodes) and can be tracked by an electro-optical camera. The DRA enables



Fig. 135.1: Image processing computer workstation interfaced with two-camera electro-optical localizer.



Figs. 135.2A to F: Instruments used in computer navigation-assisted surgeries. From left to right: (A) Spanner. (B to D) Dynamic Reference Frame. (E) Reference Tracker with reflecting sphere. (F) Navigation probe (bottom).

accurate navigation even in the presence of motion (Figs. 135.2A to F). The LEDs are called the active arrays, as the light emitted by them is recognized by the electro-optical camera. Instrumentation is accomplished by specialized instruments (screw drivers, probes, drill guides, etc.) with attached reflective spheres. The reflective spheres are called the passive arrays as they reflect the infrared rays emitted by the camera. The infrared light that is transmitted from or reflected by these instruments is relayed to the computer workstation that calculates the precise location of the instrument tip in the surgical field as well as the location of the anatomical point on which the instrument tip rests.¹⁴ The relative position of the instruments and DRA is tracked by an optical camera to facilitate navigation.

Image Acquisition

The initial step in image-guided spinal surgery is the acquisition of multiple successive images of the region of interest. Image acquisition can be preoperative or intraoperative and can be accomplished with either fluoroscopy or CT.

Preoperative CT-Based Image Guidance

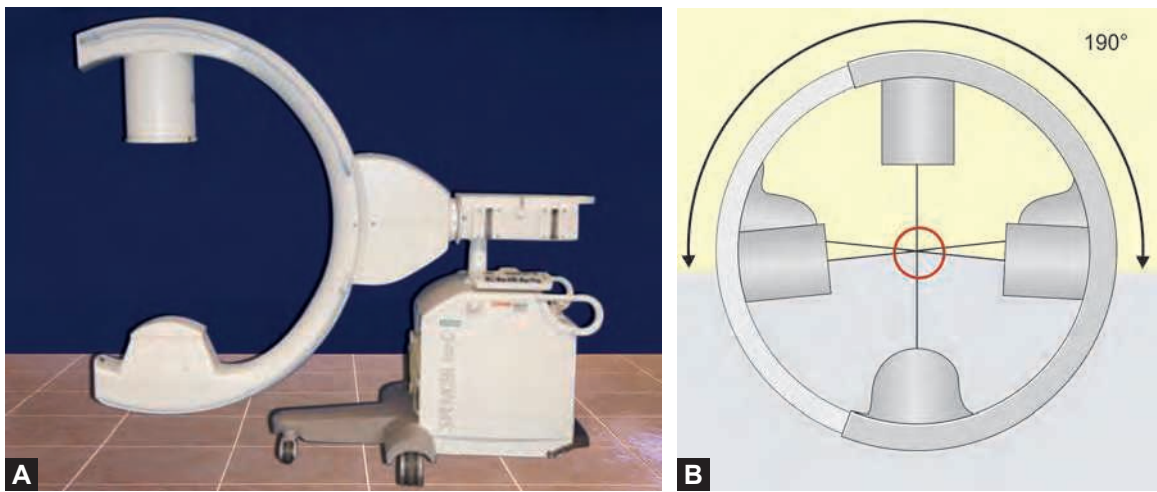
Preoperatively CT scan of the planned vertebral level is acquired using standard protocol. The images are obtained using thin, contiguous axial slices (1–3 mm). The scan data is transferred to the computer workstation. The computer workstation reconstructs the data into axial, coronal, and sagittal views of the spine.

Intraoperatively the first step of navigation is patient registration. After exposure of the spine, DRA is attached firmly to spine that is usually the spinous process. Registration is then performed using the registration probe fitted with LEDs by paired-point matching and surface matching technique. This information allows the computer workstation to create a contour map of vertebrae. The preoperative CT-based image guidance is associated with the following disadvantages:

- The need for preoperative CT scan. The scan should be performed using a specific protocol, and hence if patient already has a CT scan it will add to cost and time and also radiation exposure.
- The registration process has a learning curve and is time-consuming, and takes on an average of about 3–5 minutes.¹⁴
- Registration process needs to be repeated many time during surgery depending on the length of fixation and this affects the duration of surgical and navigational procedure.¹⁸
- The preoperative CT data is acquired with the patient in different position than at the time of operation. This could be problematic in patients with instability like trauma and degenerative instability. This may lead to movement and changes in position during intraoperative positioning leading to navigational inaccuracy.
- The process of registration paired patient matching and surface matching depends on exposed spinal anatomy. This limits its use in minimal invasive procedures.

Virtual Fluoroscopy

This is a technique that merges the standard 2D C-arm fluoroscopy with image-guided navigational technology. Anteroposterior, lateral, and oblique views are obtained with a fluoroscope with an attached calibration target. The images are then automatically transferred to the IGS that then correlates the data with the intraoperative spinal anatomy. The main advantage of virtual fluoroscopy is that it uses the standard C-arm image intensifier that is available in the operation theater and the familiarity of the surgeon to the system. In addition, virtual fluoroscopy also eliminates manual registration and reduces radiation exposure operative time. The main drawback is that the technique provides the surgeons with only anteroposterior and lateral planar images. The pedicle screw fixation depends on the position of screw in the axial plane. It is



Figs. 135.3A and B: Siemens SIREMOBIL Iso-C three-dimensional (3D) automatically rotates through a 190° arc about the patient to obtain 3D images.

important to demonstrate the relation of screw relative to the spinal canal. The quality of image is dependent on the resolution of acquired fluoroscopic images. This will be of disadvantage and can affect navigation in osteoporosis, obese patients, and deformity.

Intraoperative 3D C-Arm Fluoroscopy

This technique combines an isocentric C-arm fluoroscope with an image-guided navigational technology. Isocentricity ensures that the central focus is precisely maintained, while C-arm is moved in the angular and orbital direction. In switching between anteroposterior and lateral views, there is no need to adjust the C-arm horizontal travel in and out. Unlike a standard fluoroscope, an isocentric C-arm is able to automatically rotate around the patient through a 190° arc while maintaining the relative spinal anatomy in its center (Figs. 135.3A and B). The image can be acquired in 2 minutes cycle (100 high-resolution images) or 1 minute cycle (50 low-resolution images). The addition of specialized software Iso-C to C-arm allows this technology to effectively work as a CT scanner. The images are then reconstructed to provide axial, coronal, and sagittal views of the anatomy. The Iso-C-arm is fitted with a customized reference frame. The DRA is attached to a fixed point on the patient's spine. During image acquisition, the electro-optical camera tracks the position of DRA in relation to the C-arm during image acquisition.

The images are reconstructed in to sagittal, axial, and coronal format and then transferred to the navigation

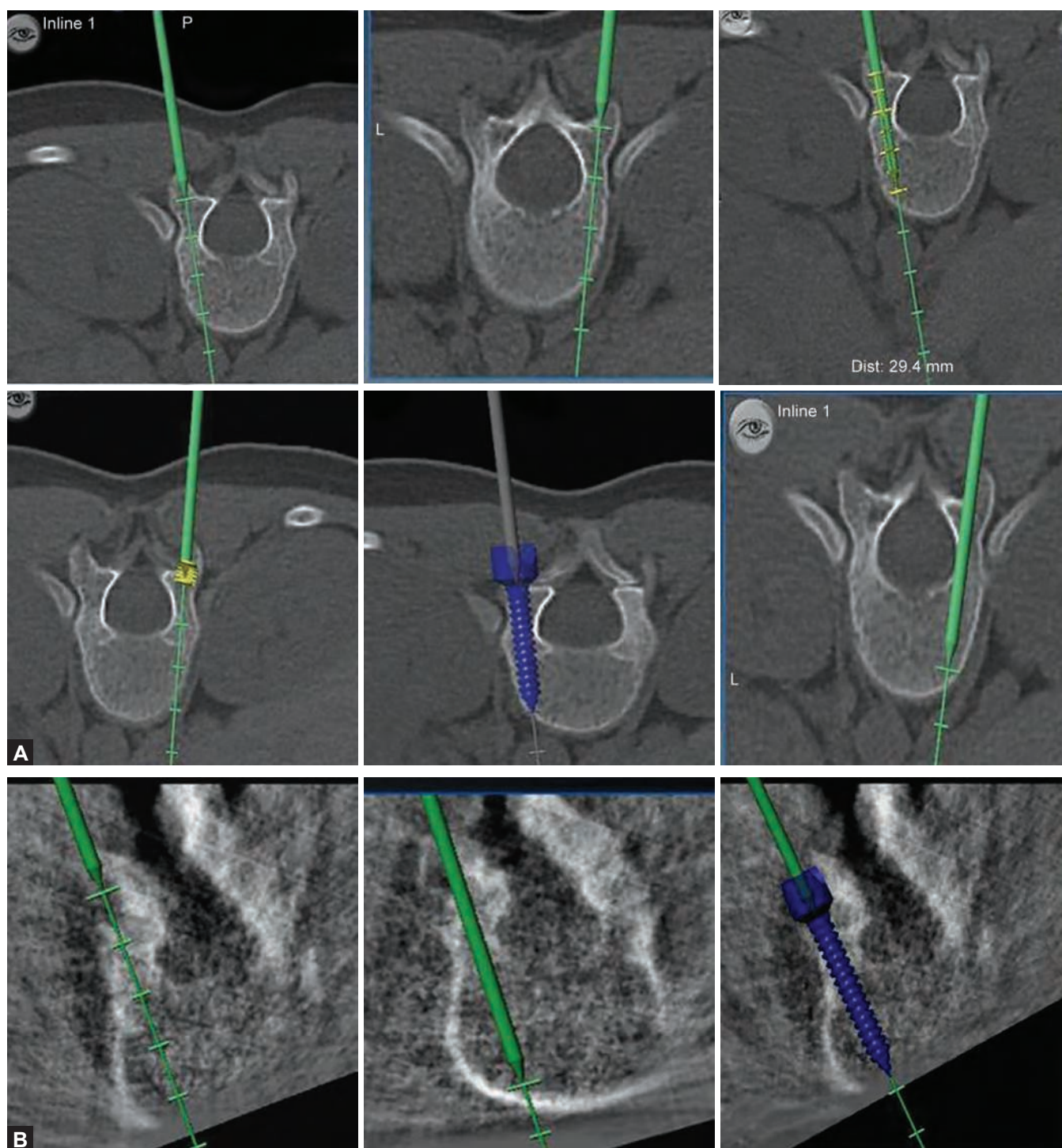
workstation. This technique allows automated registration eliminating the need for manual registration.

Advantages of Iso-C Based Navigation

- Does not require preoperative CT scan with the image-guided protocol and hence saves money.
- Since the image acquisition is intraoperative, the concern of navigational inaccuracy on positioning is eliminated.
- Automated registration eliminates manual registration and hence saves time.
- The position of implant, adequacy of tumor removal, etc. can be confirmed by obtaining a postprocedure scan intraoperatively.
- Can be used safely in percutaneous and minimal access surgery.
- The isocentric-C-arm can serve as a standard C-arm fluoroscope, allowing a single device to serve as both C-arm and during image-guided cases.

Disadvantages of Iso-C Based Navigation

- Axial reconstructions that are of lower resolution than those available with CT scans (Figs. 135.4A and B).
- Like all fluoroscopic technique, the quality of image is dependent on the resolution of acquired fluoroscopic images. This will be of disadvantage and can affect navigation in osteoporosis, obese patients, and deformity.
- The working area is only a 12 × 12 cm long segment and hence the procedure will need multiple image acquisitions.



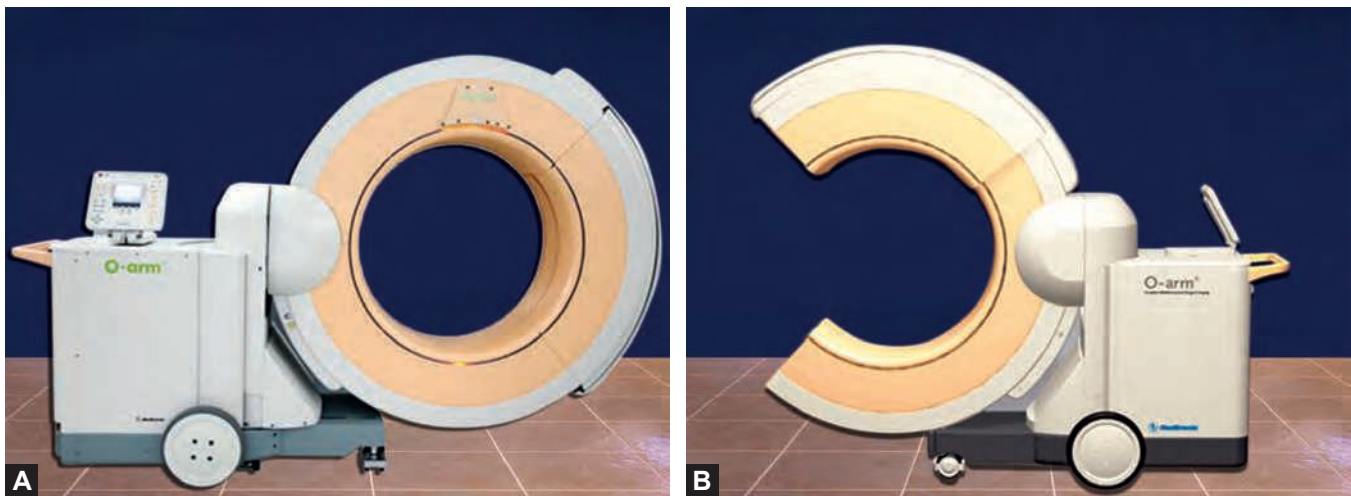
Figs. 135.4A and B: Images acquired from computed tomography-based navigation (A) and Iso-C-arm based navigation (B).

Intraoperative CT-Based Navigation

- O-arm
- Intraoperative CT suite.

O-Arm Navigation System

It is an intraoperative imaging that uses the flat panel detector technology to improve intraoperative image



Figs. 135.5A and B: O-arm navigation system with flat panel detector.

acquisition and quality. It can provide standard fluoroscopic image or 3D CT scan. The O-arm consists of an oval telescopic gantry that obtains images in a 360° arc (Fig. 135.5A and B). The O-arm gantry is automatically adjusted by a motorized robot. The X-ray tube and the flat planar are located within the oval unit. The field of view of O-arm is 30 × 40 cm, and hence it can scan up to six vertebral levels in an adult patient. The images are obtained intraoperatively, while a DRA is attached to patient. The images are transferred to a workstation resulting in multiplanar reconstruction and automated registration. Higher resolution images can be obtained with 750 pulses over 25 seconds, while reconstruction images require 391 pulses over 13 seconds.¹⁹ Postprocedure O-arm can be used as a standalone CT scanner to confirm screw placement, spine decompression, tumor resection, and alignment.

Full rotation 3D intraoperative imaging using O-arm imaging system offers the following benefits over Iso-C based 3D navigation:

- Faster rotation time results in shorter image acquisition time
- Improved resolution and thus higher quality images
- Larger field of view
- *Reduced radiation exposure:* The radiation exposure is about (2.09–5.45 mGy) for spine that is much less than conventional CT.

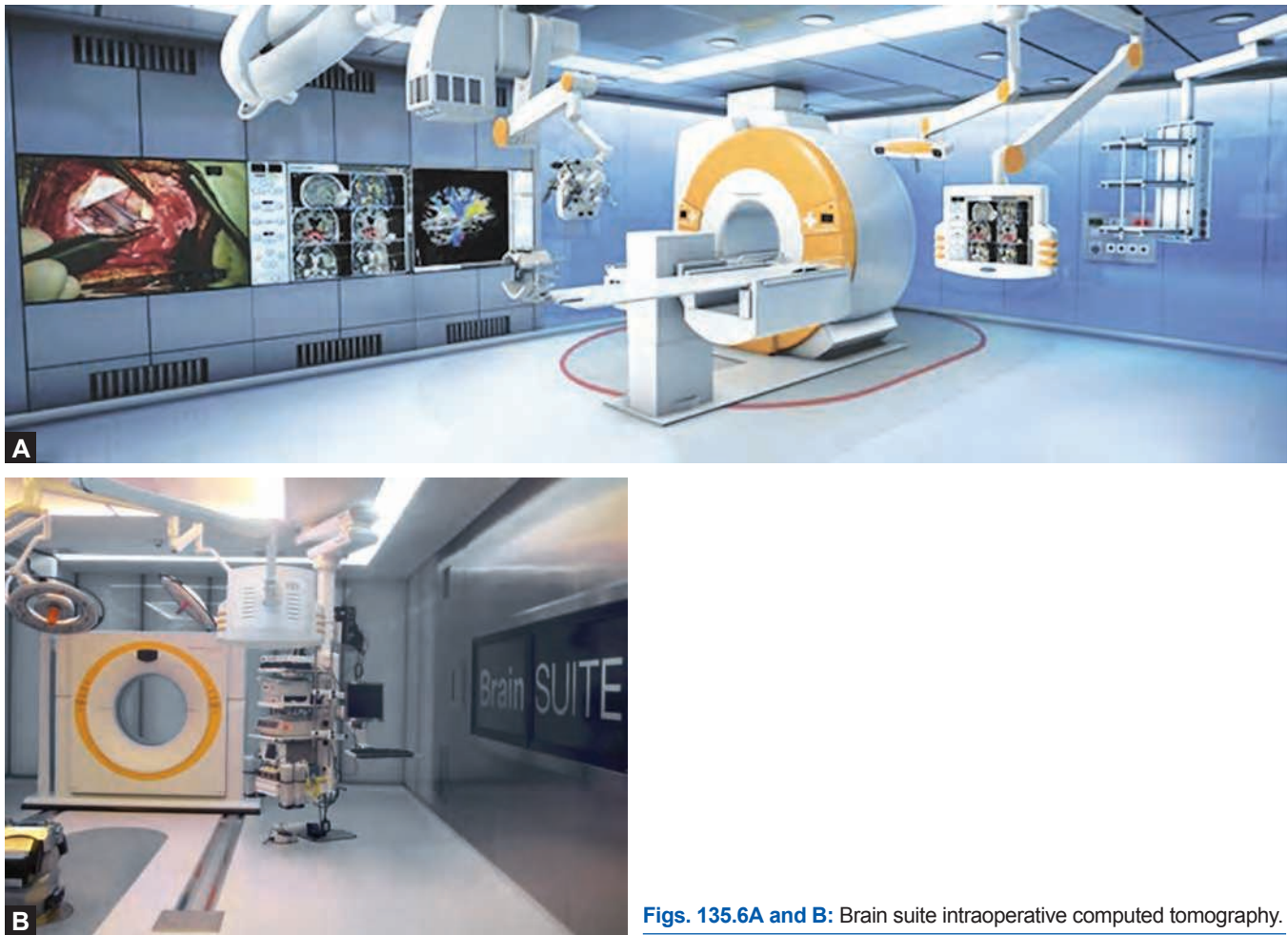
Brain Suite Intraoperative CT

Brain suite by Brain lab combines VectorVision sky navigation with an intraoperative CT scanner and operating

table with a radiolucent table top (Figs. 135.6A and B). The CT scanner is a sliding 40 slice gantry with an enlarged bore diameter of 82 cm. The image data is transferred directly from scanner into the navigation system. This technology makes it possible to anatomically register images taken intraoperatively. It allows enhanced decision process by improving surgical navigation, planning, data management, integration, and image registration. The intraoperative CT (iCT) navigation allows easy navigation with high accuracy. The data acquisition time is short and can acquire CT data of the whole spine. The iCT can replace an additional preoperative scan and is useful to assess spinal correction and osteotomy. The comparison between various navigation systems is shown in Table 135.1.

Reference System

The accurate translation of spatial information into detailed renderings of spinal anatomy necessitates a stable frame of reference that enables the IGT computer to calculate the relative positioning of instruments within the surgical field in all three dimensions, usually with a consistent magnitude of error of no more than 2–3 mm.^{20,21} The registration process serves to establish a precise spatial relationship of the image data with the physical space of patients corresponding surgical anatomy.²² The registration process can be performed either with the tracking device (fixed position marker) or without the tracking device (fiducial marker).



Figs. 135.6A and B: Brain suite intraoperative computed tomography.

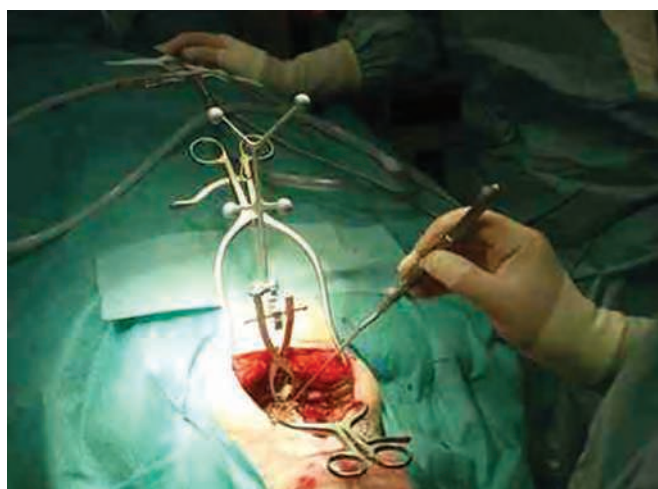
Fiducial markers are attached to multiple distinct anatomic landmarks that serve as registration points. Then the paired point registration is performed by selecting at least three corresponding points in a CT and in the exposed anatomy. Increasing the number of points will enhance the accuracy of the registration process but is associated with increased duration. This is usually combined with the surface matching as a supplementary registration technique. Surface matching involves selecting multiple points on the exposed surface of the spine in surgical field (Fig. 135.7). This information is transferred to a workstation, and a topographic map of selected anatomy is created and matched to the patient and to the patient image set²². In a long level fixation necessitating multiple registration processes, the duration of navigated procedure will be significantly prolonged. Image-guided navigation without tracking device is subjected to patient movement either by respiration or leaning on the table.

The spinal tracking device consists of passive reflectors mounted on a small frame. This reference frame is attached to exposed spinal anatomy that is usually the tip of spinous process and its position is tracked by infrared camera system. Any movement of the spinal anatomy alerts the navigation system that makes appropriate calculation to maintain accuracy. This when used with fluoroscopic and iCT-based image acquisition can perform an automated registration. This technique involves attachment of a reference frame on the exposed spine and a second reference frame on the fluoro or the CT scanner. Once the image is acquired, the data is transferred to the navigational system that then performs an automated registration eliminating the need for manual registration. The disadvantages are the need for maintaining a line of sight between the reference frame and optical camera, hindering of the movement of the surgeon, and displacement of the reference frame that will affect the accuracy of navigation.

Table 135.1: Comparison between various navigation systems.

<i>Image-guided surgery</i>	<i>2D fluoroscopy</i>	<i>3D fluoroscopy</i>	<i>Preoperative computed tomography</i>	<i>O-arm</i>	<i>Intraoperative</i>
Registration	Automated	Automated	Manual and time-consuming	Automated	Automated
Registration duration	Short	Short	Long	Short	Short
Image display	2D [anteroposterior (AP) and lateral]	3D	3D	3D	3D
Scan time	Only AP and lateral radiographic images	2 minutes	30 seconds	40 seconds	30 seconds
Number of vertebrae in single scan	3–5 vertebrae	3–5 vertebrae (working area 12 × 12 cm)	Whole spine	6–8 vertebrae (working area 30 × 40 cm)	Whole spine
Bone image quality	Poor	Poor	Good	Good	Good
Imaging in severe deformities	Not possible	Not possible	Possible	Possible	Possible
Carbon table and carbon head clamp fixation	Not necessary	Required	Not necessary	Required	Required
Ideal area of the spine	Lumbar spine	Whole spine	Whole spine	Whole spine	Whole spine
Minimally invasive spine surgery	Difficult	Possible	Not possible	Possible	Possible
Real-time imaging	Yes	Yes	No	Yes	Yes

(2D: Two-dimensional; 3D: Three-dimensional).

**Fig. 135.7:** Surface matching.

Tracking System

Image-guided navigation utilizes either optical or electromagnetic (EM) tracking systems. The optical localizer tracks infrared light emitted by a series of LEDs mounted on a customized handheld navigational probe or selected

surgical instruments. Alternatively, the optical localizer itself can be the source of infrared light that is continuously reflected back to the camera by passive reflectors attached to the probe or selected surgical instruments²² The successful function of these optical systems is dependent on a clear “line-of-sight” between the tracking device and the surgical field, so hand movements that disrupt this connection will impede the navigation process (Fig. 135.8).

In the EM system, three orthogonal EM fields are generated by a transmitter attached to a fixed anatomic reference point such as a spinous process. The positional data of these instruments are collected by a receiver and is integrated by the computer processor to facilitate navigation.²¹ The main advantage is that an unobstructed view between the transmitter and receiver is not required, allowing the surgeon and nursing staff to work freely within the operative field. The disadvantages include interference of EM image guidance by metal artifact and EM fields originating from operating room equipment (e.g. monopolar electrocautery, electrocardiogram monitoring). Because of the limited area of these EM, the transmitter needs to be repeatedly transferred to obtain sufficient tracking information for multilevel procedures.



Fig. 135.8: Intraoperative theater setup of navigation gadgets. The dynamic reference array (red arrow) has been attached to the patient's spine and kept horizontal to be seen by the optical localizer system (green arrow). The Iso-C C-arm rotates around the operative site capturing multiple images that are then transferred to the localizing platform.

Technique of Navigated Pedicle Screw Fixation

The first step in navigation is registration. After registration, the accuracy of registration is confirmed by placing the navigational probe on the exposed surface land marks like spinous process, lamina, transverse process and moving the probe on the lamina. The computer workstation should display the probe tip touching corresponding points on the CT data. If the position of probe on the patient and computer do not match, there is registration and localization error and the whole process of registration should be repeated. This verification step represents a more absolute indicator of registration accuracy and is important to perform prior to proceeding with navigation. After the verification step has been completed, the spinal anatomy previously hidden from direct surgical view is now easily visualized on the workstation monitor in multiple planes. When the navigational probe is placed directly perpendicular to the long axis of the spine the image will be in the sagittal, coronal, and axial plane. The reformatted image will change depending on the angle between the navigation probe and spine. As the probe is moved to a different location, the reformatted image and trajectory line will change (Figs. 135.9A to D). Thus, the navigated

system will provide better anatomical information of the spine. Instruments used for pedicle screw fixation can be precalibrated or intraoperatively calibrated. Precalibrated instruments are automatically recognized by IGS and are immediately available for use. Intraoperative calibration needs registration of each instrument for it to be recognized by the IGS and hence it is time-consuming (Figs. 135.10A to D).

The probe is used to confirm the starting point of pedicle screw fixation and pilot holes are made with a high-speed burr or awl to enter the cortex. The estimated trajectory and recommended size of the implant are superimposed on multiplanar images of the selected level. The surgeon makes a mental note of this trajectory and instrumentation proceeds in a standard manner. At each stage of instrumentation that precedes insertion of the pedicle screw, the trajectory of the implant can be confirmed with the specialized probe. The integrity of the pedicle wall can be confirmed by a pedicle feeler.

Advances in Spinal Navigation

Spinal planning software iPlan spine developed by Brain lab is a surgical planning software to create a strategic treatment plan for procedures performed with spinal navigation and tumor surgery. The software uses multiple data-sets such as CT and magnetic resonance imaging (MRI). Preoperative CT-MRI merging helps in detailing the bone and soft tissue extent of tumors and hence it is resection.

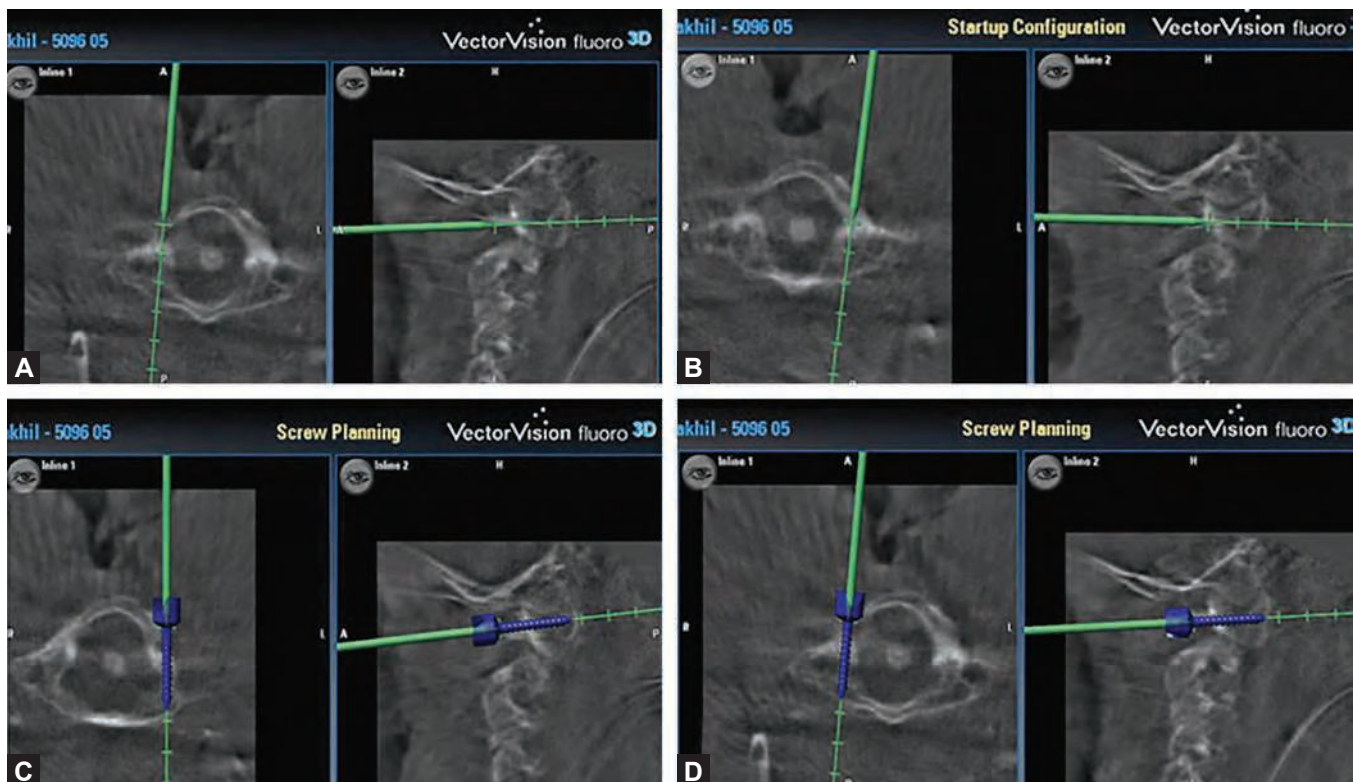
The current navigation systems collaborating with implant manufactures provide navigation ready pedicle instruments, K-wires, and drill guide to make instrumentation simpler and faster.

Concerns of Spinal Navigation Surgery

Even though spinal navigation has been existent for about two decades, it is yet to gain general acceptance among surgeons. This lack of acceptance has been attributed to increased operative time, learning curve, and complexity of navigation. The concerns in spinal navigation surgery are accuracy, operative time, radiation, learning curve, and cost-effectiveness.

Accuracy

The demands concerning the accuracy of image-guided procedures vary depending on the type of procedures, e.g. ventral or dorsal, anatomy of the spine (normal curvature



Figs. 135.9A to D: Workflow of navigation: the navigation probe helps to ascertain the exact entry point for a screw (A), the direction and trajectory of the screw (B) and the width and the length of the screws (C and D).

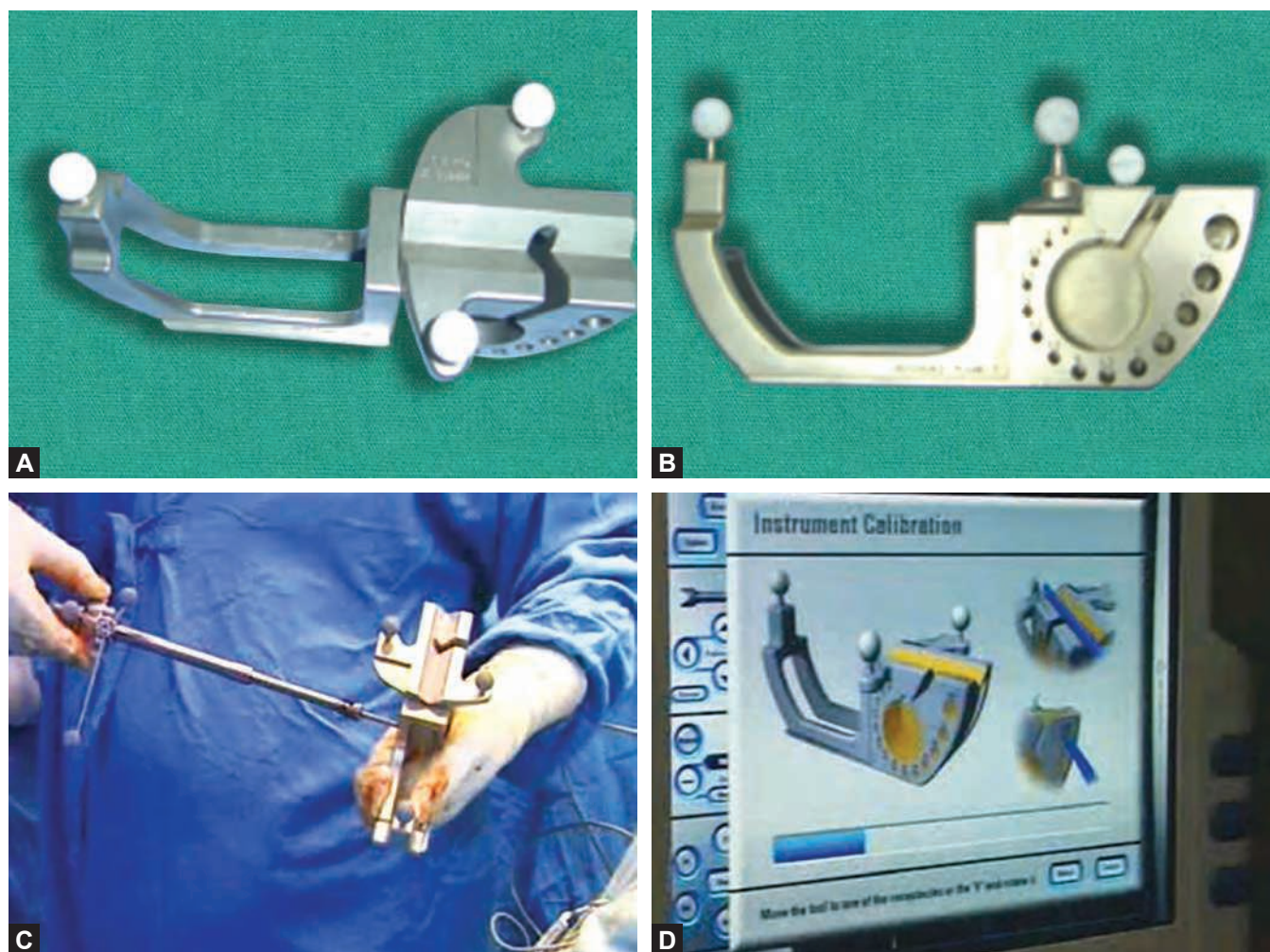
or deformed), and the level of the spine subjected to surgery. In the cervical spine, the overall accuracy is very good with a maximum displaced rate of 8% reported by Acosta et al.²³ compared to 22% of misplaced screws in conventional techniques. The displacement rates of 8% may be attributed to the small size and complex anatomy of the pedicles, resistance offered by the musculature while inserting screws and the relative mobility of cervical spine during the procedure.

In the thoracic and lumbar spine, navigation-based studies have shown pedicle perforation rates between 1% and 5%. Silbermann et al.²⁴ reported a higher accuracy rate by 5% points for pedicle screw placement using O-arm navigation compared to 2D fluoroscopy/CT group (99% vs. 94.1%). Tian et al. have shown that 3D-based navigation system (CT and 3D Iso-C based navigation) provides more accurate pedicle screw insertion over 2D fluoroscopy-based navigation system.²⁵ The superiority of navigation system is more obvious when they were applied to abnormal spinal structure. Overall image-guided surgery increases the accuracy of pedicle screw placement but

does not completely prevent instrumentation misplacement. This has been attributed by Tjardes to the human factor involved in IGS, i.e. the surgeon.²⁶

Operative Time

One of the major concerns with the use of spinal navigation is the increased operative time. The time taken to insert a pedicle screw using IGS depends on experience of the surgeon, familiarity with the navigation system, the registration process, and the need for single or multilevel registration. The use of automated registration process using Iso-C C-arm and iCT has shortened the duration of the procedure significantly. A meta-analysis by Shin et al.²⁷ showed no difference in the operating time between navigated and non-navigated pedicle screw. Patil et al. reported a mean time for screw placement of 5.9 minutes using navigation that was slightly longer than previously reported for screw placement using conventional techniques (5.1 minutes) but shorter than the preoperative CT navigation method, 7.5 minutes per screw.²⁸ Rajasekaran et al. reported a significantly shorter time required to insert



Figs. 135.10A to D: The calibration guide and intraoperative calibration of the pedicle screw.

a pedicle screw using 3D Iso-C-arm in scoliosis. In their study, the average screw insertion time in the non-navigation group has 4.61 ± 1.05 minutes compared to 2.37 ± 0.72 minutes in the navigation group.²⁹ Shin et al. have shown that the mean time for insertion of a pedicle screw was 3.79 minutes in the fluoroscopy guided group and 4.45 minutes in O-arm navigation-guided group.³⁰ The mean preparation time for screw placement was about 19 minutes in navigation-guided group, compared to only 4 minutes in fluoroscopy-guided group.

The iCT, as a result of its ability to allow for multiple level registration, significantly reduces the time for pedicle screw insertion and therefore mean total operative time in comparison with single level registration. Cui et al.³¹ in their analysis of iCT navigation noted a mean iCT scanning time of about 17 seconds for the whole spinal column and a mean time-out for intraoperative scanning of about

6 minutes. In spinal navigation combined with the intraoperative 3D imaging modality, the implantation time of the pedicle screw becomes simplified, more accurate and safe with shorter operative time.

Radiation

One of the major advantages of IGS is to minimize radiation exposure to the surgeon, assistants, and the operating room personnel. When compared to other procedures in musculoskeletal surgery, spine surgery is radiation intensive. The work by Rampersaud et al. demonstrated that for the spine surgeons, radiation exposures is up to 10–12 times greater than in other orthopedic procedures, and may approach or exceed guidelines for cumulative exposure.³² Radiation dose varies based on the total fluoroscopic time, type of machine, and the position of the

image intensifier. In IGS, there is less radiation exposure both in the amount of time of radiation exposure and in the total radiation dose that is used intraoperatively.³³

Gebhard et al. showed that image-guided approaches generally reduce the radiation exposure of the operating room personnel independent of the registration mode compared to standard fluoroscopy-assisted surgery.³⁴ The best results were found for 3D-fluoroscopically assisted approaches with a 10-fold reduction of radiation exposure compared to standard fluoroscopy-assisted procedure.³⁴ This is because that when image acquisition is being performed, the surgeon and operating room staff stand outside the theater or behind a lead shield. Of concern is the amount of radiation exposure to the patient. In the preoperative CT-based image-guided navigation system, because of the necessity for thin-sliced, high-resolution CT scans, the overall radiation exposure to the patient is significantly higher. This can be reduced by using an optimized sequential CT protocol. The new-generation scanner, by using new technologies like dose modulation, tube current modulation, and filtering, uses less radiation. The amount of irradiation of O-arm is only 60% of the ordinary CT scan (data from Medtronic, USA).

Cost-Effectiveness

The use of IGS adds to the cost of surgery. This is particularly applicable to iCT-based systems that will need radiation shielding, a larger operating room, and additional trained staff. The reduced incidence of neurological injury and reoperation rate, especially in complex anatomical areas like the cervical and upper thoracic spine, and complex pathologies like deformities and tumor, should offset some of the cost. The combination of IGS and minimally invasive spine surgery (MISS) may reduce the overall morbidity of spinal surgery with less surgical dissection, reduced hospital stay, early mobilization, and early healing. The economic study on the use of IGS by Costa et al. revealed a mean reduction of costs of about 17.7% per surgery when using navigation. This difference was mainly noted in the reduction of the operative time (about 30 minutes for the procedure) and the costs of pre- and post-operative CT scans.³⁵

Learning Curve

The concerns about the learning curve using IGS including accuracy and operative time have created some reservation about adapting to this technology. A survey of 147 spine surgeons regarding spinal navigation found that

the major weaknesses were longer operative time (63.5%), increased cost (48.3%), lack of necessity (40.7%), unreliable navigation accuracy (37.9%), and intraoperative glitches (35.2%).³⁶ However, it has been our experience that the surgical time decreases significantly after gaining familiarity with IGS. Wetzel et al. in a case cohort study demonstrated decreased screw perforation rate and operative time. The learning curve showed a drop after 6 months of using IGS that plateaued after 12 months. The majority of IGS education takes places in the OR, and the development of education and training modules using navigation technology will offer a way to develop and improve the capabilities to perform IGS.

Other Limitations of IGS

The movement of the reference frame by respiration and muscle retraction can result in erroneous information regarding spinal position, resulting in misplacement of an implant. The surgeon or the assistant may touch the DRA during the procedure causing loss of connection and movement of the frame. This can be prevented by fixing the DRA to a rigid stable bony structure such as spinous process or pelvic ring. Also, it is important that the accuracy check be repeated many times during the procedure to confirm the accuracy of the registration process. The movement of the surgeon between the DRA and the optical camera can interfere with navigation. This has been addressed by having ceiling-mounted optical cameras.

Clinical Applications of Spinal Navigation

The application of IGS navigation provides allows for improved understanding of surgical anatomy and facilitates the accuracy of implant placement. In addition, IGS also reduces the stress on the surgeon performing these complicated procedures. The experience of the surgeon and the complexity of the procedure are two important factors determining intraoperative surgical stress. Wetzel et al. in their paper on the effect of stress on surgical management reported that intraoperative stress affects judgment, decision making and communication. Studies have shown that the detrimental effects of these factors are related to errors and poor surgical outcome.³⁷

The spinal navigation technique was initially used to enhance the safety of pedicle screw insertion. In the past decade, refinements and advances in the technology have extended the use to decompressive procedures, deformity correction, tumor resection and minimally invasive

surgery (MIS). This has been largely possible due to the capability to merge the preoperative CT and MRI via the navigation system and the use of special precalibrated tools like an awl, screw driver, osteotome and k-wire drill guide.

Spinal Instrumentation

Pedicle screw fixation has gained acceptance as an effective and reliable method of spinal instrumentation. Pedicle screw fixation allows for multidimensional control and provides greater rigidity and improved fusion rates. Initially used in the lumbar spine, their use has extended to the thoracic and cervical spine. However, because of variation in the pedicle anatomy and the small size of the thoracic and cervical pedicle, the safe and precise placement of pedicle screws can be difficult. Despite the use of intraoperative fluoroscope and electrophysiological monitoring, the incidence of screw malposition remains high even in experienced surgeons. Various studies have shown that the pedicle violation can vary between 14% and 55% using standard techniques.³⁸ The accurate placement of pedicle screws is critical for successful outcomes. The malposition of pedicle screws carries risk to the neural elements, vascular injury, reoperation and pleural effusion associated with misdisplacement.^{39,40} Although many clinical studies report a low incidence of neurological injury associated with misplaced screws, there is evidence that small cortical breaches can impact the biomechanical strength of a construct.⁴¹

George et al.⁴² demonstrated the importance of cortical containment of pedicle screws in their findings that the pull-out strength of pedicle screws with a cortical breach was 11% less than that of screws contained wholly within the pedicle. The additional anatomic data provided by IGS improves the accuracy of pedicle screw fixation and reduces the risk of neurologic and vascular injury. Also, image guidance allows larger diameter screws to be placed and can result in screws being placed in a more medial trajectory resulting in increased construct stability.

Kosmopoulos et al.⁴³ in a meta-analysis showed that the rate of cortical violation by pedicle screws inserted without the use of navigation amounted to nearly 10%.

Cervical Spine Instrumentation

The instrumentation of the upper cervical spine has certain inherent problem due to the smaller size of osseous elements, higher incidence of anatomic variation, inconsistent landmarks in complex congenital anomalies and

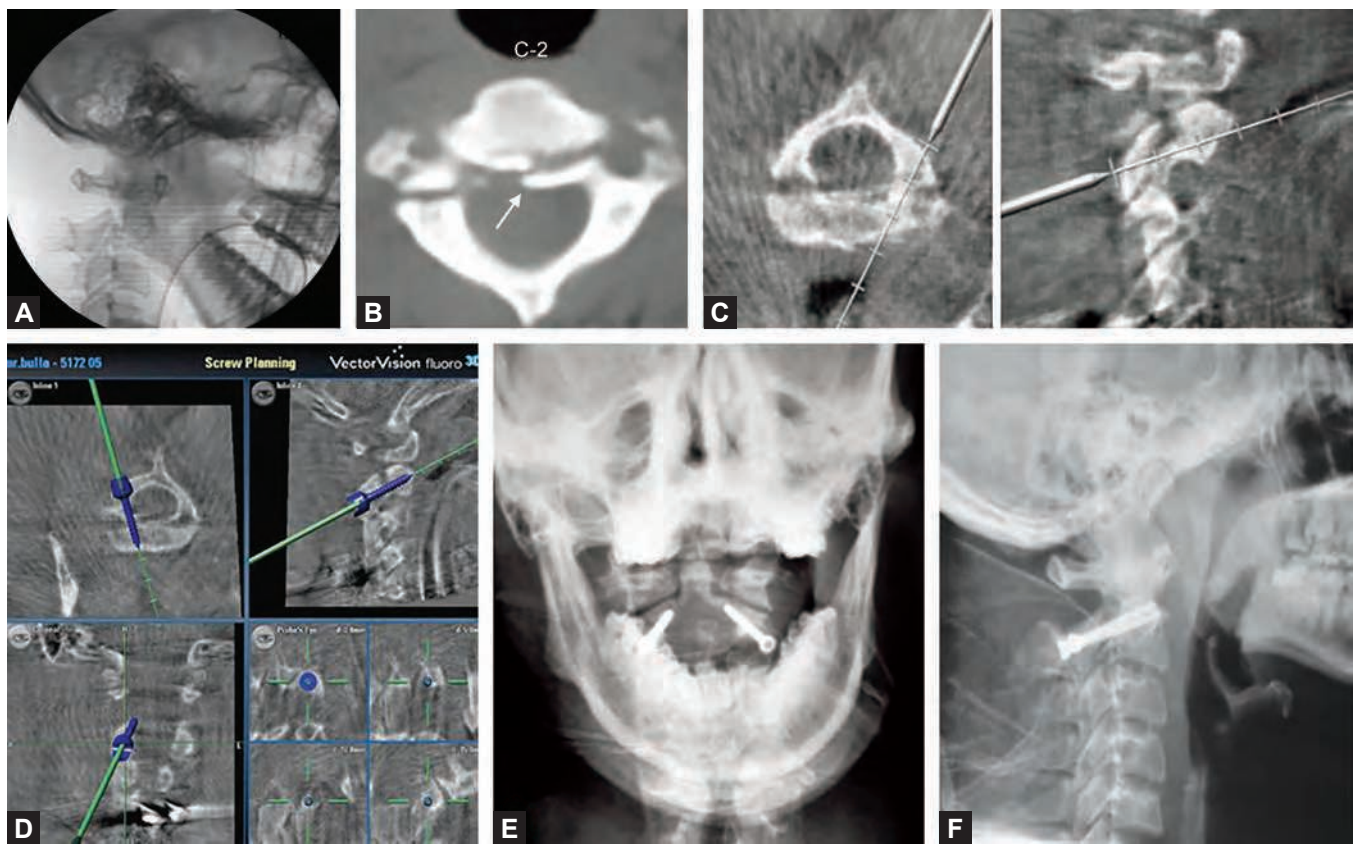
close proximity of vital neurovascular structures.⁴⁴ The C1–C2 transarticular screw provides higher fusion rates but is contraindicated in about 20% of patients due to variation in vertebral artery anatomy.⁴⁵ C2 pedicle screw placement theoretically should avoid injuring the vertebral artery. However, the presence of a high residing C2 transverse foramen, vertebral artery erosion of the pedicle and an anomalous vertebral artery increases the risk of injuring the artery. In a multicenter study on C1–C2 fusion in 102 adult patients, Aryan et al. were not able to identify the C2 pedicle in 23 patients (22%). The vertebral artery also had a variable course in >25% of these patients, forcing them to use alternative methods of fixation.⁴⁶

Application of IGS in Upper Cervical Spine

- C1–C2 transarticular fixation
- Segmental C1–C2 screw fixation
- Anterior odontoid screw fixation
- Transoral surgery
- Direct repair of a hangman's fracture.

Bolger and Wigfield,⁴⁷ in a retrospective review, did not observe any neurological or vascular injuries following C1–C2 transarticular screw placement performed using navigation. Marcus Ritcher et al.⁴⁸ analyzed 22 patients following C1–C2 transarticular screw placement using navigation. The screw position was evaluated postoperatively using CT with multiplanar reconstruction along the screw axis of each screw. None of the transarticular screws or pedicle screws were significantly (>2 mm) misplaced and no screw-related injury to vascular, neurogenic or bony structures were observed. No screw revisions were necessary. Rajasekaran et al.⁴⁹ and Attia et al.⁵⁰ have reported on the efficacy of navigation for screw fixation following traumatic atlantoaxial injury in children. C1–C2 rotatory instability is associated with rotation of C1 and C2, leading to alteration in normal anatomical landmarks and orientation. In a prospective study of 20 patients, Rajasekaran et al.⁵¹ demonstrated the safety of Iso-C navigation in the direct repair of the pedicle in hangman's fractures. Bilateral screw fixation was possible in 18 patients and the remaining 2 had unilateral screws because of significant fracture comminution. There was no screw malposition with all 20 patients showing evidence of fusion at an average of 8 weeks (Figs. 135.11A to F).

Yang et al.⁵² in a retrospective study compared anterior odontoid screw fixation between Iso-C based navigation and standard technique. The fluoroscopy time in the Iso-C 3D group was 42.9 seconds as compared to 68.1 seconds in the control group ($P < 0.01$). The mean operative time



Figs. 135.11A to F: Navigated direct repair of Hangman's fracture. Lateral radiograph image and axial computed tomography shows a hangman's fracture (A and B). The intraoperative navigation image shows the fracture line and the planned screw trajectory and dimensions (C and D). Postoperative anteroposterior and lateral images show the reduced fracture has been fixed with pedicle screws. (E and F) Pedicle-based cortical screws.

was 91.5 minutes in the Iso-C 3D group compared with 81.6 minutes in the control group ($P = 0.20$). The procedure required the DRA to be attached to the Mayfield clamp for registration. Image guidance in anterior odontoid screw fixation obviates the need for cumbersome biplanar fluoroscopy allows for intraoperative image acquisition after surgical exposure, reduces intraoperative registration time, reduces both surgeon and patient radiation exposure and allows immediate computerized topographic imaging in the operating room to verify screw position.⁵³ The authors have also used Iso-C navigation in the reduction and fixation of unstable C1 burst fractures with good results. Iso-C based navigation assisted in confirming intraoperative reduction of the fracture, identifying the screw entry point and the direction of C1 lateral mass screw trajectory and final screw position.

Cervical pedicle screw provides significantly greater stabilization and stronger pullout strength than lateral

mass screws. They are ideal fixation points in patients with severe deformities of the cervical spine such as in rheumatoid arthritis that may require correction of a complex cervical deformity.⁵⁴ The complex anatomy of the normal cervical spine including the narrow diameter of the pedicles, the variations in the sagittal and axial angulations of the pedicles as well as the anatomical variations in the course and size of the vertebral artery makes cervical pedicle screw instrumentation a challenging procedure. Abumi et al.⁵⁵ using conventional techniques reported a perforation rate of 6–7% (45 of 664 screws) with 2 screws causing radiculopathy. Kotani et al.⁵⁶ compared navigated and non-navigated pedicle screws placement and found reduced rates of pedicle screw breaches (6.7% vs. 1.2%) in the navigated group. There was a 2% complication rate in the manual group, whereas the navigated group had no adverse events. Ishikawa et al.⁵⁷ and Ito et al.⁵⁸ using image-guided pedicle screw placement reported a screw

malposition rate of 2.8% with no neurovascular complications.

Rajasekaran et al.⁵⁹ performed a prospective study evaluating the accuracy of pedicle screw placement in children with cerebral palsy with complex cervical deformities. Of the 55 cervical pedicle screws placed, 88.3% were fully contained, 11.7% had a noncritical breach and none had a critical breach. Rajan et al.⁶⁰ demonstrated that in cervical deformity, of the 98 cervical pedicle screws placed using navigation, there was a high rate (90.8%) of what they termed “perfectly placed screws” leading them to conclude that the Iso-C 3D technique increased the accuracy of screw insertion.

In contrast to several reports demonstrating an advantage of a navigation system in the improvement of accuracy, there have been some criticisms of its effectiveness. Ludwig et al.⁶¹ experimentally compared the accuracy of manual insertion with computer-assisted screw placement, demonstrating no significant improvement in the computer-assisted group. This may have been due to the fact that the instrument guide tube with light-emitting diode was navigated only on the surface of the lamina, and the actual tip of the awl and screws were not directly visualized on the navigation monitor during each step of the screw insertion. We have found that the use of calibrated instruments for cervical pedicle screw insertion provides accurate, 3D and real-time instrument tip information, serving as an effective tool for safe and reliable pedicle screw placement in the cervical spine.⁵⁶

The results of the above mentioned studies clearly demonstrate that spinal navigation reduces but not eliminate the risk of screw malposition.

Thoracic Spine Instrumentation

Thoracic pedicle screws are an optimum anchor points because of their biomechanical superiority, increased tolerance of corrective force application and sparing of motion segments. However, thoracic pedicle screw placement in the upper and mid-thoracic spine is challenging due to size constraints. In the thoracic spine, the pedicles are narrow and the canal cord ratio is low; hence, the chance of a pedicle violation causing cord injury is common. Even in the normal thoracic spine the difficulty in obtaining high-quality intraoperative anteroposterior, lateral fluoroscopic view adds to the complexity of pedicle screw fixation.

Vaccaro et al.³⁸ placed 90 screws in the T4–T12 pedicles of five fresh-frozen cadavers and determined that 41%

violated the pedicle wall. Various studies using freehand technique pedicle screw placement have demonstrated a 14–55% misplacement rate and 1–8% neural injury due to malposition.^{39,40,43} Kim et al.⁶² examined the feasibility of IGS placement of thoracic pedicle screws in cadavers; while the overall rate of cortical screw perforations was 19.2%, the accuracy of the procedure increased considerably as the learning curve was overcome. Kosmopoulos et al.⁴³ performed a meta-analysis of the current literature and found that navigation provided higher accuracy in the placement of pedicle screws for the subgroups presented. Overall, the placement accuracy in the in vivo navigation-assisted subgroup (95.2%) was higher than that in the un-navigated subgroup (90.3%). The report included 130 studies with a total of 37,337 implanted pedicle screws.⁴³ Comparing 2D and 3D navigation systems Tian and Xu reported that CT navigation resulted in a higher accuracy rate than 2D navigation but provided a lower accuracy than the 3D fluoro group.⁶³

Shin et al.²⁷ conducted a meta-analysis of perforation risk for computer navigated versus freehand insertion. The study included 20 studies and a total of 8,539 screws (4,814 navigated and 3,725 non-navigated). In their analysis, there was a significant lower risk of pedicle perforation for image guided pedicle screw insertion than that for non-navigational insertion for all regions of the spine with an overall pedicle perforation risk of 6% for IGS and 15% for non-navigational insertion. The meta-analysis importantly did not reveal a significant difference in total operative time when comparing the two techniques.

Larson et al.⁶⁴ in their study, demonstrated a lower accuracy rate for pedicle screw placement with navigation in children compared with adults (96.4% vs. 98.2%). They hypothesized that the lower accuracy rate in children may be due to small pedicle size and possibly greater deformity.

■ DEFORMITY SURGERY

Application in Thoracic Spine Deformities

Pedicle screw instrumentation is the preferred method of posterior stabilization of the spine especially in the presence of deformity. It has the advantages of three column fixation, improved coronal, sagittal, and rotational correction, lower incidence of implant failures when

compared with conventional hook and wire constructs. In the presence of deformity, the size and orientation of the thoracic pedicles vary considerably between the different vertebrae within the curve, and also between the concave and convex sides of the same vertebrae. The pedicles are frequently thinner and sclerosed, making canal perforation a significant problem. The dura is often stretched over the pedicles on the concave side of the curve, and even minor medial violations can damage the cord. Hence, pedicle screw instrumentation is challenging as there are potential risks of iatrogenic damage to neural or vascular structures. Hicks et al.⁶⁵ in a systematic review of complications of pedicle screw fixation in scoliosis surgery, found a malposition rate of 15.7% per screw inserted confirmed with postoperative CT scans. Modi et al. reported that only 73% of the screws were accurately placed in 37 neuromuscular scoliosis patients with a mean Cobb's angle of 82° using the freehand technique.⁶⁶ Also, the reported reoperation rate in the literature due to implant malposition is about 5% in deformity correction surgeries.⁶⁷

Fortunately, the use of IGS has shown to improve the accuracy, decrease the operative time, and the radiation exposure in these complex surgeries. Navigation also allows safe insertion of pedicle screws by the in-out-in technique in pedicles that are sclerosed and too thin to accept a screw.

A study by Laine et al. on a 100 patients, including a small number of spinal deformity patients, demonstrated that the screw perforation rate significantly decreased from 13.4% to 4.6% with the use of computer navigation in the thoracic and lumbar spine.⁶⁸

Rajasekaran et al.²⁹ performed a randomized controlled trial that compared navigated (Iso-C 3D-based) and non-navigated placement of pedicle screws in scoliosis. They looked at 27 patients with scoliosis and 6 with kyphosis, with a total of 478 screws being inserted. Pedicle screw accuracy was much better in the navigated group with only a 2% breach rate compared with 23% in the non-navigated group. Additionally, the screw insertion time was much less in the navigated group, 2.37 ± 0.72 minutes compared with 4.61 ± 1.05 minutes in the non-navigated group including the time required for the C-arm to be moved into the operative field (Figs. 135.12A to F).

In a comparative study on the accuracy of pedicle screw placement in scoliosis between conventional fluoroscopic and computer-assisted surgical techniques, Kotani et al.⁵⁶ observed a perforation rate of 11% in the conventional group and 1.8% in the navigated group.⁶⁹ The improved

accuracy of intraoperative CT-based IGS in the insertion of pedicle screws in deformity has been demonstrated in the recent papers by Cui et al.³¹ and Larson et al.⁷⁰ Larson et al. reported on the use of O-arm based navigation in pediatric congenital deformity and reported a 99.3% screw accuracy rate.

The advances in spinal navigation techniques, such as planning software and precalibrated instruments, have made it possible to extend the use for correction of complex of deformities through vertebral osteotomy techniques. Fujibayashi⁷¹ demonstrated the safety and utility of computer-assisted surgical planning and image-guided surgical navigation in the planning and execution of major osteotomies in order to correct severe kyphoscoliosis. The IGS and CAS (computer-assisted surgical) planning significantly reduced the difficulty of operating through the fusion mass when planning both the osteotomy and pedicle screw placement (Figs. 135.13A to D).

Application in Cervical Spine Deformities

The presence of a deformity and altered anatomy (due to congenital anomalies) adds to the difficulty in performing cervical pedicle screw fixation. A study by Kotani et al.⁵⁶ of 17 patients, most of who had a cervical deformity, demonstrated a reduced screw perforation rate using computer navigation from 6.7% to 1.2%. Rajasekaran et al.,⁵⁹ as previously mentioned, again demonstrated improved screw accuracy placement in children with cerebral palsy and cervical deformity. He noted that of the 55 screws placed, 88.3% were fully contained, 11.7% had a noncritical breach and none had a critical breach (Figs. 135.14A to I). Rajan et al.⁶⁰ showed that in cervical deformity, of 98 cervical pedicle screws placed using navigation, there was a high rate (90.8%) of what they termed "perfectly placed screws" leading them to conclude that the Iso-C 3D technique increased the accuracy of screw insertion. There are certain limitations of Iso-C based navigation in deformity surgery. In case of severe deformity, it is difficult to centralize the patient in both anteroposterior and lateral view using C-arm. In gross obesity, the arc of C-arm cannot move freely around the patient. In these situations, intraoperative CT navigation offers an advantage over Iso-C arm navigation. The iCT is an especially effective imaging modality in complex cervical deformity and may decrease reoperations due to implant malposition.³¹



Figs. 135.12A to F: Navigation in scoliosis. Navigation can be used to insert pedicle screws into deformed and rotated vertebrae with good accuracy. In this patient with idiopathic scoliosis of 58° magnitude, intraoperative Iso-C navigation-guided pedicle screws have been used to correct the deformity.

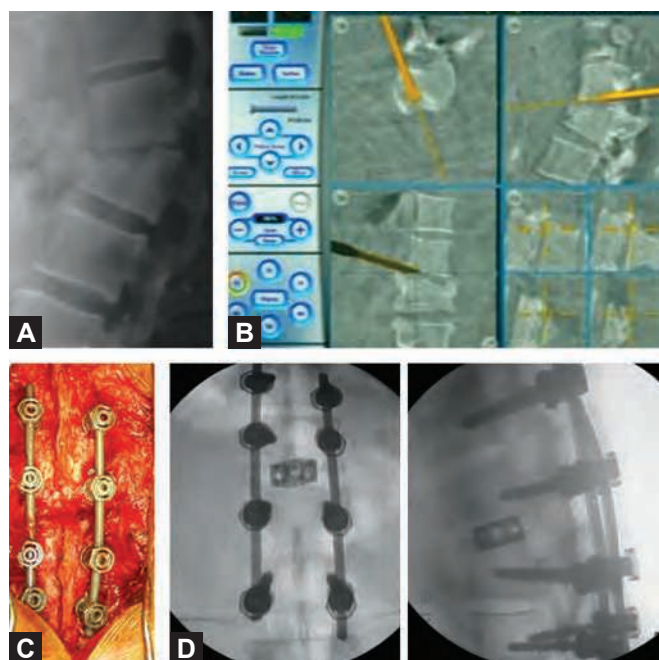
Lumbar Spine

Lumbar fusion surgeries have continued to evolve with clinical outcomes showing promising results. This has resulted in high number of instrumented fusion, with pedicle screws being the most common form of fixation. As in the thoracic and cervical regions, the placement of lumbar pedicle screws carries a risk of injury to nerve root if it breaches the inferior and medial pedicle wall or it can cause injury to dura and neural elements if the screw is angulated medially excessively. If the size of screw is too long, it can cause injury to the anteriorly lying vessels, leading to catastrophic intraoperative bleeding and vascular shock. Schulze et al.⁷² reviewed postoperative CT

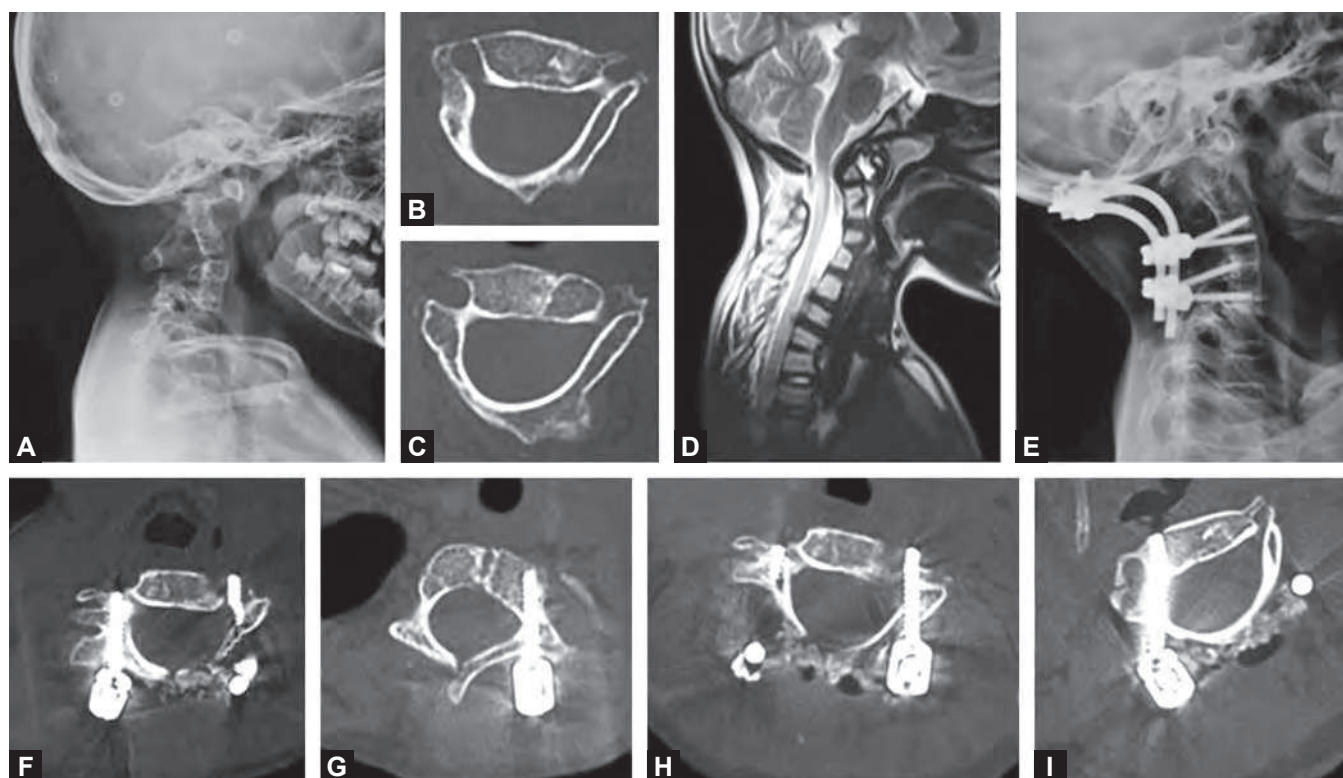
scans in a series of patients who underwent lumbar fusion procedures by experienced surgeons not using navigation and reported a 20% screw perforation of the pedicle wall.

Amato et al.⁷³ reported in 2010 on the accuracy of pedicle screw placement in the lumbosacral spine using conventional open techniques and intraoperative fluoroscopy followed by postoperative CT in 102 consecutive patients. The rate of frank pedicle screw misplacement was 5% of which two patients had radicular pain and a neurological deficit.

The concept for applying image guided therapy (IGT) to lumbar pedicle screws was established in a laboratory study by Foley and Smith. They performed a cadaver study using image guidance and demonstrated via postoperative



Figs. 135.13A to D: Navigated correction of post-traumatic deformity. Lateral radiograph demonstrates a post-traumatic thoracolumbar deformity (A). Intraoperative navigation images demonstrate the planned osteotomy level (B). Intraoperative picture (C) and postoperative radiographs show good correction of the deformity (D). Postoperative anteroposterior and lateral radiographs show good correction of the deformity.



Figs. 135.14A to I: Cervical pedicle screw instrumented occipitocervical fusion in an 8-year-old child. (A) Lateral radiograph of the cervical spine showing cervical segmentation anomaly with atlantoaxial instability. (B and C) Axial computed tomography (CT) images showing atypical attenuated dysmorphic pedicles at C3 and C4 levels. (D) Sagittal MRI of the cervical spine showing atlantoaxial instability with cord compression at the craniocervical junction. (E) Lateral X-ray of the cervical spine shows reduction of atlantoaxial instability with subaxial cervical pedicle screws and occipitocervical fusion. (F to I) Axial CT images showing well-contained cervical pedicle screws without any pedicle breach at C3 and C4 levels.

CT scans and visual inspection no evidence of pedicle wall violation. Kalfas et al.¹⁴ using image guidance inserted 150 lumbar pedicle screws in 30 patients and found that 149 of the screws were placed satisfactorily. Several clinical investigations have also affirmed that computerized image guidance may be a viable strategy for facilitating transpedicular instrumentation in the lumbar spine.

In 2002, Laine et al.⁶⁸ studied the accuracy of image-guided lumbar instrumentation in their prospective, randomized clinical trial involving 100 subjects and nearly 500 pedicle screws. Postoperatively, the incidence of pedicle perforations was significantly lower in the IGT cohort compared with the control group whose screws had been implanted with a conventional technique (4.6% vs. 13.4%, respectively). Resnick⁷⁴ employed virtual fluoroscopy in 23 lumbar arthrodesis procedures and determined that in 96 of 97 cases the pedicle probe was in either an ideal or acceptable position, corresponding to a 99% positive-predictive value relative to traditional fluoroscopic visualization. In a retrospective clinicoradiological study, Costa et al.³⁵ reported an accuracy rate of 91.8% with preoperative CT-based navigation as against an accuracy rate of 95.2% with intraoperative CT acquisition. They also noted that intraoperative CT navigation and subsequent automerging of the anatomy allowed a significant reduction in operative time.

Disc Replacement Surgery

Long-term function of lumbar artificial discs depends on the optimal positioning in the sagittal and the frontal plane. McAfee et al.⁷⁵ in a clinical study of 100 patients, reported that 17% of the cases demonstrated a suboptimal (3–5 mm deviation) or bad (>5 mm deviation) position of the implants, necessitating eventual revision surgery. Smith et al. in 2006⁷⁶ performed a cadaver-based study of lumbar disc arthroplasty prostheses comparing IGS-guided prosthesis placement with biplanar C-arm. The image-guided technique appeared to increase the accuracy of prostheses placement in the coronal plane and improved their rotational alignment, while decreasing the degree of interprocedural variance and minimizing radiation exposure of the surgeon. This has also been confirmed by Rauschmann et al.^{77,78} in their cadaveric study comparing a conventional surgical technique with the use of a navigation. Marshman et al. in 2007 reported the first clinical study that demonstrated significantly improved accuracy of lumbar total disc arthroplasty placement via

postoperative CT using IGS compared with conventional fluoroscopy. They recommended the routine use of IGS during lumbar total disc arthroplasty.

Revision Surgeries

Revision spinal surgeries pose a great challenge to the surgeon because important anatomic landmarks may be obscured or even absent secondary to scar tissue formation, bony deformities, and other postoperative changes. In addition, the tactile feedback from native cortical and cancellous bone is lost. The presence of pre-existing hardware further poses a surgical challenge, often complicates the placement of subsequent implants, and alternative strategies may need to be considered in revision cases where there have been prior attempts at internal fixation.

Austin and coworkers⁷⁹ compared two methods of image guidance to an open technique for the insertion of pedicle screws in a cadaveric model of posterolateral thoracolumbar fusion. According to their analysis, the rates of pedicle perforation were 21.4% following laminoforaminotomy, 8.33% for fluoroscopic IGT, and 0% with CT-based navigation. Rampersaud and Lee reported⁸⁰ a 20% breach rate in 102 pedicle screws placed through mature fusion masses in revision spine surgery cases using 2D fluoroscopy-based image guidance.

Lim et al.⁸¹ performed a retrospective review of 78 patients with a prior lumbar fusion who underwent CT image guidance revision surgery. They reported a 4.1% cortical violation rate with no clinically apparent radicular pain or weakness. No pedicle screws required revision for malpositioning, and they concluded that the accuracy rate of stereotactic image-guided pedicle screw placement into a previously fused lumbar spine is 96%. A study by Nottmeier et al.³³ of 102 patients undergoing revision surgery under image guidance demonstrated a pedicle cortical breach rate of 7.8%. This was lower than that described by Rampersaud and Lee who used 2D image guidance, but higher than that reported by Lim et al. who used 3D image guidance.

Seichi and coworkers⁸² observed no neurological or vascular injuries in their series of revision cervical procedures (4 C1–C2 transarticular screws and 47 pedicle screws) performed using a frameless stereotactic IGT system, although the authors noted that the risk of sustaining a cortical breach was considerably higher when the reference frame arc could not be adequately fixed to the distorted vertebral body.

Application in Ventral Spine Surgery

Albert et al.⁸³ assessed the feasibility of using image-guided stereotaxy in performing anterior cervical corpectomy in a cadaveric-based study. The average distance from the lateral border of the trough to the medial border of the foramen transversarium in the standard trough group was 5.10 mm (range, 1.72–7.71 mm), and the average distance from the medial border of the foramen transversarium to the image-guided trough was 4.34 mm (range, 3.34–5.48 mm). Their study concluded that image guidance provided improved accuracy when compared with that of standard techniques, implying the clinical potential for image-guided corpectomy.

Klein et al.⁸⁴ assessed the feasibility of using an image-guided Kerrison punch when performing an anterior cervical foraminotomy. The authors were able to determine the distance of the Kerrison tip to the vertebral artery. Their study concluded that an image-guided Kerrison punch may be used successfully when performing cervical foraminotomies during an anterior cervical discectomy, thus eliminating the risk of potential vertebral artery injury.

Assaker et al.⁸⁵ were the first to describe a ventral image-guided procedure in the thoracic spine for the removal of a calcified thoracic disc herniation that was removed thoracoscopically.

Computed tomography based navigation system was used by Kim and coworkers⁸⁶ for treating thoracic disc herniations. The authors used the costotransversectomy technique and reported no neurologic or vascular complications as well as a complete decompression of the neural elements verified postoperatively with advanced imaging modalities.

Seichi et al.⁸⁷ reported the safety and efficacy of IGT-assisted anterior thoracic decompression in three patients with ossification of the posterior longitudinal ligament that were successfully treated through a thoracotomic approach. Ohmori et al.⁸⁸ reported the application of an image-guided approach to ventral decompression and corpectomy in three cases of thoracolumbar vertebral collapse.

The optimal fixation of the DRA to the spine remains an unsolved problem in ventral decompression procedures. The available options are fixation to the iliac crest, spinous process or transthoracically on a long stylus directly into a vertebral body. Problems with stable fixation exist with fixation to the iliac crest, limited visibility using navigation system if fixed to a spinous process or the problem of an obstructing object in the thoracic cavity if the Dynamic Reference Array (DRA) is fixed to a vertebral body.

Thoranaghatte et al.⁸⁹ have tried to address this problem by the hybrid navigation system that uses the endoscope as the tracking device. A fiducial marker is fixed to the spine and the position and orientation of the marker in space is determined by means of image analysis. This information is then correlated to the position of the endoscope, which is equipped with a DRA. This technique, which is still under evaluation, could obviate the need for a DRA.

Navigation in Minimally Invasive Surgeries

Percutaneous placement of pedicle screws is becoming routine in spine surgery with the advent of minimally invasive techniques. The reported benefits of minimally invasive techniques compared with open procedures include reductions in blood loss, length of hospital stay, infection rates, postoperative pain and time to return to work.⁹⁰

Minimally invasive pedicle screw fixation is associated with increased radiation exposure to the patient, surgeon and staff, along with higher risk of a misplaced screw. Studies have reported cortical breaches during percutaneous pedicle screw placement exceeding 15%,^{80,91,92} with neurological injury as high as 15%. Computerized navigation is ideally suited for MIS because these systems provide essential spatial and anatomic data without requiring any direct visualization of the spine itself. Three-dimensional fluoroscopy utility has been well established in various minimally invasive techniques such as TLIF (transforaminal lumbar interbody fusion), posterior fusion procedures, kyphoplasty and thoracic discectomy.

Initially, cadaveric studies were done using navigation for safety and accuracy. Sasso et al.⁹³ in 2005 evaluated the percutaneous placement of translaminar facet screws with the use of virtual fluoroscopy as an image guidance technique. No screws were placed in the spinal canal or in contact with the exiting nerve root and accurate screw placement was confirmed in all specimens.

Kim et al.⁶² in 2008 reported on a feasibility study of image-guided percutaneous pedicle screw fixation. They reported an average 12.4 milli-REM (mREM) of radiation exposure delivered to the surgeon during a unilateral MIS TLIF procedure without navigation (FLUORO group), whereas radiation exposure was undetectable in the navigation group. The total fluoroscopy time was also higher for the FLUORO group compared with the NAV group

(41.9 seconds vs. 28.7 seconds). No statistically significant differences were noted for operating time, estimated blood loss, or hospital stay. Li et al.⁹⁴ studied navigated percutaneous pedicle screw fixation in thoracolumbar fractures and reported a surgical time of 2.1 hours that was significantly shorter than that of the conventional pedicle screw fixation group (2.7 hours). Yang et al.⁹⁵ and Idler et al.⁹⁶ in two separate prospective studies concluded that the use of guidance reduces fluoroscopy and insertion times with increased accuracy compared with conventional fluoroscopic methods of percutaneous pedicle screw insertion. Jako et al.⁹² in a cadaveric demonstrated increased accuracy of percutaneous screw placement and reduced radiation exposure by means of a novel EM navigation system. The use of EM field navigation avoids the cumbersome line-of-sight issues of the optical-based systems, thus facilitating minimally invasive percutaneous procedures.

Villavicencio et al.⁹⁷ reported on the use of Iso-C 3D based navigation in 279 screws in 69 patients. Accuracy, operative time, and amount of fluoroscopic utilization time were assessed for TLIF and kyphoplasty cases. They concluded that use of intraoperative 3D fluoroscopy for image guidance in minimally invasive complex spinal instrumentation procedures is feasible and safe.

Balloon kyphoplasty is an accepted option after conservative treatment has failed to reduce the pain associated with osteoporotic vertebral fractures. The patient can be mobilized 24 hours after the procedure, and in most cases, pain is considerably attenuated or completely disappeared. Depending on the patient, the experience of the performing surgeon, and the level of the fractured vertebra, the average patient effective radiation dose during a balloon kyphoplasty procedure can be > 12 mSv. This radiation dose is three to four times higher than a full-body CT scan. In challenging cases of deteriorated anatomy and difficult radiomorphologic orientation, especially of the lower thoracic spine, image-guided kyphoplasty succeeds in finding the optimal pedicular approach to the vertebral body, helps to avoid collateral damage, and minimizes the overall risk of the procedure.⁹⁸ Izadpanah et al.⁹⁹ demonstrated significant reduced operating time and radiation dose in the navigated kyphoplasty group. The average radiation time was reduced significantly in the navigated group (99 seconds thoracic and 74 seconds lumbar). Radiation exposure to the patient was also significantly lower using image guidance (1,245 cGy cm² thoracic and 1,318 cGy cm² lumbar).

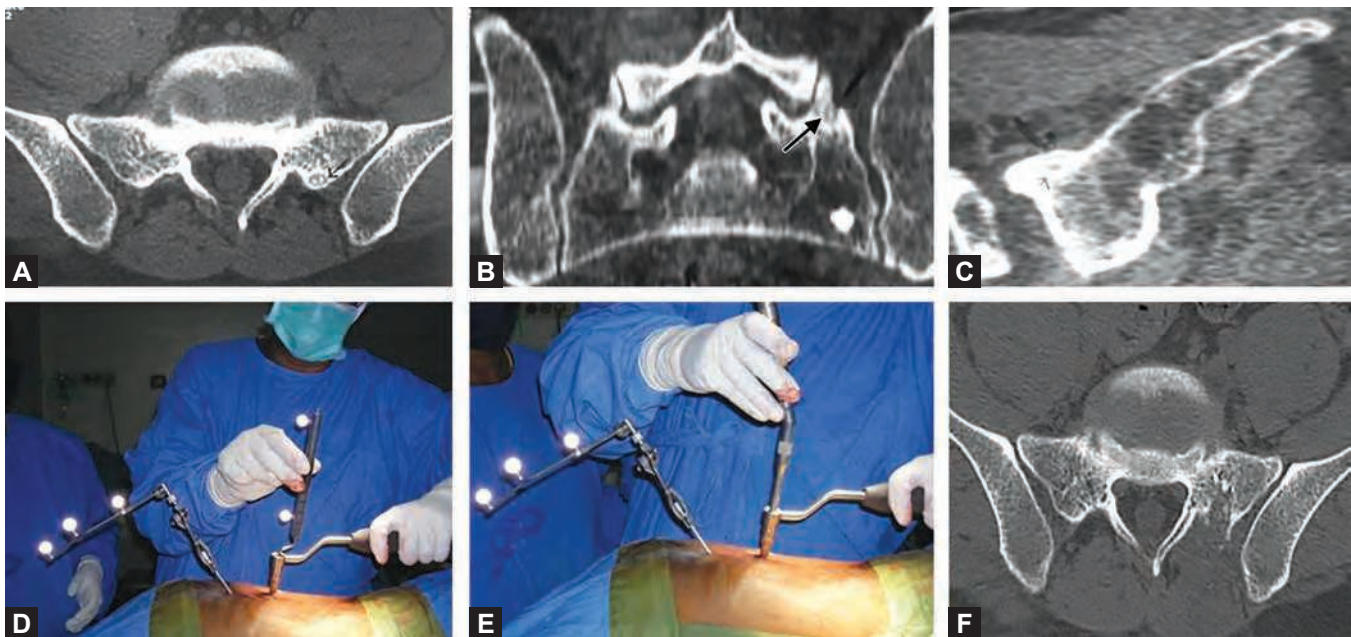
Johnson et al.⁹² evaluated quantitatively the application of frameless stereotactic image guidance in thoracoscopic discectomy procedures in 16 patients, who underwent image-guided thoracoscopic discectomy. Accuracy determined by registration (calculated) and navigation (intraoperative) was 1.7 and 1.2 mm, respectively. They concluded that image-guided thoracoscopic spinal surgery can provide 3D orientation to a 2D imaging procedure that ultimately improves accuracy, efficiency, and safety.

The evolving technology and the combination of intraoperative navigation and minimally invasive technology have allowed for the development of innovative operative treatment methods for addressing spinal pathology. MacMillan¹⁰⁰ has reported on an excellent 2-year results following computer-aided trans-sacral arthrodesis with percutaneous interbody fixation across the L5-S1 disc space. Webb et al.¹⁰¹ in a cadaveric study demonstrated the feasibility for performing minimally invasive direct lateral interbody fusion. However, additional studies will be needed to evaluate the efficacies of these approaches and validate many of the purported advantages.

Tumor Excision

Performing bone tumor resection using a navigation system can improve the accuracy of the surgical resection and help preserve function. Under navigated guidance, 3D anatomy of the tumor and the surrounding normal tissue can be visualized during surgery. Precise control of the resection margin is possible, enabling one to achieve the resection margin determined preoperatively. In selected patients, this technique can be helpful in increasing the accuracy of surgical resection and in reducing functional impairment. The key problem is that for successful navigation both soft tissues and bony structures need to be registered simultaneously. This prerequisite is not yet met in spinal tumor surgery. A possible solution is the development of navigated smart tools that interact with soft tissues only in the direct vicinity of the dissection without changing the spatial distribution of the surrounding tissue.²⁶

The efficacy of image guidance in pedicle screw placement in metastatic tumors has been proved by various authors.¹⁰² Arand et al. did a clinical study on the accuracy of CT-based decompression and insertion of pedicle screws in patients who have had tumor-related posterior surgery of the thoracic spine. In all eight patients accurate decompression of the spinal canal was seen. Eighty-six percent (19 of 22) of the navigated pedicle screws were positioned centrally in the bone. However, registration



Figs. 135.15A to F: Iso-C navigated percutaneous excision of sacral osteoid osteoma. Preoperative axial computed tomography (CT) images (A to C) show an osteoid osteoma (black arrow) of the sacrum. The osteoid osteoma is localized using the probe Nidus is marked by a black arrow mark. (D) and excised using a drill (E). Postoperative CT image (F) shows complete excision of the tumor.

errors can happen in the presence of significant bony destruction of the vertebrae necessitating safe fixation of the DRA away from the chosen vertebrae. Therefore, image-guided approaches should only be chosen in those cases where the DRB can be attached close to the vertebra being operated as distant fixation might result in significant registration errors.

Image-guided surgery helps in safe removal of certain benign bony tumors without destabilizing the spine. Rajasekaran et al.¹⁰³ reported on the efficacy of Iso-C 3D intraoperative spinal navigation in excising osteoid osteomas in four patients. A minimally invasive reflective array, tool navigator, and a registered burr were used for localization and deroofing of the lesion, followed by curettage and high-speed burring of the cavity. Complete removal of the nidus was confirmed intraoperatively by reacquisition of data (Figs. 135.15A to F). Conservation of bone allowed early mobilization and also removed the need for reconstruction. The authors concluded that intraoperative Iso-C 3D navigation is useful in accurately localizing and guiding complete excision of spinal osteoid osteomas through a minimally invasive approach without compromising spinal stability. The efficacy of this procedure was confirmed by van Royen et al.³ who confirmed the complete

removal of a radionuclide enhanced osteoid osteoma after 3D image-guided extirpation.

SUMMARY

Image-guided navigation surgery by linking image data to intraoperative spinal anatomy provides the surgeon with orientation to unseen anatomy, thus improving the safety and accuracy of spinal surgery.

Image guidance systems provide high accuracy of screw placement and safety for patients undergoing spinal stabilization in all areas of the spine. As the technology continues to advance, image guidance is becoming more user-friendly to the surgeon with little or no radiation exposure to the surgeon and the operating room staff. The clinical benefits of IGS for pedicle screw placement in terms of increasing accuracy and reduced radiation exposure have been clinically proven for spinal instrumentation. Navigation provides an effective method of applying instrumentation of spinal deformity and helps avoid potential complication due to implant malposition. The use of navigation in tumor surgery, minimally invasive spine surgery, and anterior spine surgery is evolving.

It is important that the surgeon develops a competency with this technology both intraoperatively with other

surgeons experienced with its use as well as in the laboratory. Image-guided surgery-based education in a skill laboratory setting helps to improve the locomotive capabilities necessary to perform safe and accurate surgery on the spine. However, it is important to remember that technology is not a substitute for a thorough knowledge of spinal anatomy and open methods of spinal instrumentation. Image-guided surgery serves as an additional source of information that can be used to make safe decisions intraoperatively.

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